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Assessing the phytosanitary protection of cereal crops in the Bouira region (Northern Algeria)

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Abstract

The Bouira region has a significant potential for cereal cultivation, covering 65.90% of the total agricultural area. Traditionally, cereal growers have relied on pesticides to control pests, but it is vital to evaluate how these practices align with the principles of cognitive sustainability. This study explores the phytosanitary practices used in cereal cultivation within the Bouira Region and assesses their impact on sustainable agricultural practices. Based on interviews with cereal growers in Bouira's central agricultural areas – El Asnam, El Hachimia, and Ain Bessam – the research was conducted during the 2023/2024 cereal season. The cereals grown include durum wheat, common wheat, barley, and oats, with routinely applied pesticides. Twenty-three pesticides protect these crops and enhance yields, herbicides being the most common, followed by fungicides and insecticides. However, the study found that protective measures were insufficient, as farmers often rely solely on masks and gloves when handling pesticides without fully understanding the associated risks. These findings underscore the urgent need for increased awareness and technical support to boost agricultural productivity and fully integrate cognitive sustainability principles, thereby fostering a more informed and sustainable approach to agriculture that safeguards both environmental and human health.

Keywords: Cereals, Pesticides, Phytosanitary, Cereal Growers, Bouira.

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1. Introduction

Cereals are vital and strategic in Algeria, accounting for around 80% of the country's utilised agricultural area (UAA), including fallow land. Every year, 3 and 3.5 million hectares are devoted to growing these cereals, underlining their crucial role in the country's agriculture and economy (Djermoun, 2009; Salim & Khã, 2021). In Algeria, most cereals are grown using traditional agricultural methods (Ait–Slimane-Ait-Kaki, 2008). Farmers use chemicals such as pesticides, which can have negative environmental impacts, including soil and water contamination. However, agricultural policy is important in supporting Sustainable Development Goals, which require adopting precision agriculture principles. These principles aim to reduce the use of pesticides, fertilisers, and water while improving soil productivity (Biró & Toldi, 2022).

The province of Bouira has made significant progress in quality and quantity in the agricultural sector. It has significant cereal-growing potential, with an agricultural area of 293,544 hectares, representing 65.90% of the total area of 445,434 hectares, according to ANIREF-Bouira (Lamri et al., 2022). This requires using various plant protection products to ensure optimum agricultural production.

However, the indiscriminate and massive use of pesticides represents an environmental and public health challenge on a global scale (Carvalho, 2017; Gressel et al., 2004). In Algeria, we still know very little about the phytosanitary protection methods used by farmers. The few surveys that have been carried out have revealed unusual practices and the use of various unauthorised pesticides in certain regions (Mebdoua et al., 2017; Soudani et al., 2020).

Our work aims to present the current state of pesticide use in cereal crops in the Bouira region. It focuses on aspects related to crops and cereal farmers, lists the products used, their methods and doses, and assesses farmers' understanding of and sensitivity to pesticide use's environmental and health risks.

2. Materials and methods

The study was conducted in the Bouira region, which was chosen for its important role in cereal production in Algeria. The specific areas selected for the survey include the provincial capital (Bouira) and the municipalities of El Asnam, El Hachimia, and Ain Bessam. These areas were chosen due to their diversity in terms of land dedicated to cereal crops, as shown in Figure 1. These sectors represent different agricultural contexts, providing an overview of agricultural practices in this region.

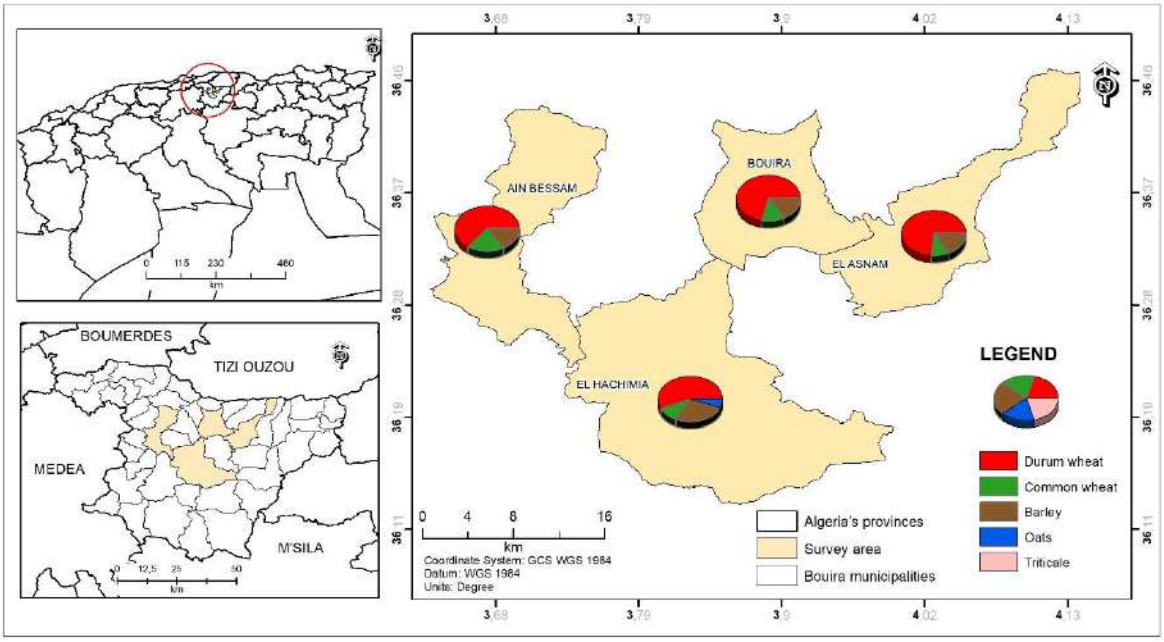

Figure 1 The survey area location and the different cereal acreages

The selection of respondents specifically targeted cereal farmers. Farmers were chosen based on their farms' size, access to pesticides, and level of involvement in cereal production. This choice ensures that the sample is representative of the overall agricultural practices in cereal cultivation in the studied region.

A total of 100 respondents participated in this study. These respondents are cereal producers who own or manage farms of various sizes and use pesticides. The diversity of respondents allows for a broad range of agricultural practices and approaches to the environmental and health challenges associated with pesticide use. The survey was conducted using a

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structured questionnaire designed to gather information on agricultural practices and the use of pesticides. This questionnaire included several key sections:

- Presentation of the farmer: general information about the owner, their area of study or agricultural training, and the size of the farm.
- Identification of the pesticides used: pesticides, fungicides, herbicides.
- Application methods and doses: information on product application methods and quantities used.
- Awareness and understanding of environmental and health risks associated with pesticide use: assessment of farmers' understanding of the potential impacts of pesticide use on the environment and health, as well as the management of empty packaging.

Data were collected in the field during the 2023/2024 cereal season through direct farm visits. During these visits, face-to-face interviews were conducted with the farmers. This allowed for more detailed responses and clarification of certain aspects of the questionnaire. Most farmers completed the questionnaires themselves, but in some cases, the researchers assisted them in ensuring a proper understanding of the questions.

The responses obtained from the questionnaires were analysed to extract trends regarding pesticide use and awareness of risks. The quantitative data concerning cultivated areas and the products used were compiled into tables, such as Table 1, allowing for comparison between the different study areas.

Table 1 Area under cereals in the area studied in 2023/2024

species	The area under cereal crops (Ha)			
	Bouira	El Asnam	El Hachimia	Ain Bessam
Durum wheat	3717.50	2560	5587	5159
Common wheat	747.25	387	1035	1834
Barley	792	550	2904	1207
Oats	31	3	500	60
Triticale	00	00	20	00
total	5287,75	3500	10046	8260

The data in Table 1 describe the distribution of cereal crops in the different studied areas (Central Bouira, El Asnam, El Hachimia, Ain Bessam), indicating the area of each type of crop (durum wheat, soft wheat, barley, oats). These figures provide a better understanding of agricultural activity and production in these regions and the emphasis placed on durum wheat production in the sector.

3. Results and discussion

Our results show a variable distribution of age groups and levels of education, with a predominance of middle-aged farmers and a high level of secondary education in some stations. As far as crops are concerned, durum wheat dominates in all localities, with regular use of pesticides to combat disease and pests. Herbicides dominate. However, there are shortcomings in the use of personal protective equipment and the management of empty packaging.

3.1. Age and level of education of farmers surveyed

In all the localities inspected, we found that all age categories were present, except for Ain Bessam, where the [21–30] and [61–70] age categories were not recorded. In fact, in this station, the age categories [31–40] and [41–50] dominate, with rates of 40% and 46.67% respectively. It is also worth mentioning that the [21–30] age group accounts for only 13.33% in El Asnam and El Hachimia (Fig. 2).

Similarly, various levels of education are present in all the localities, with varying proportions. In the localities of Ain Bessam and El Asnam, 40% of the surveyed farmers have a secondary education level. In Bouira Centre, the university education level is dominant, with a rate of 33.33%. In El Hachimia, farmers with no education have the highest rate (53.33%) (Fig. 3).

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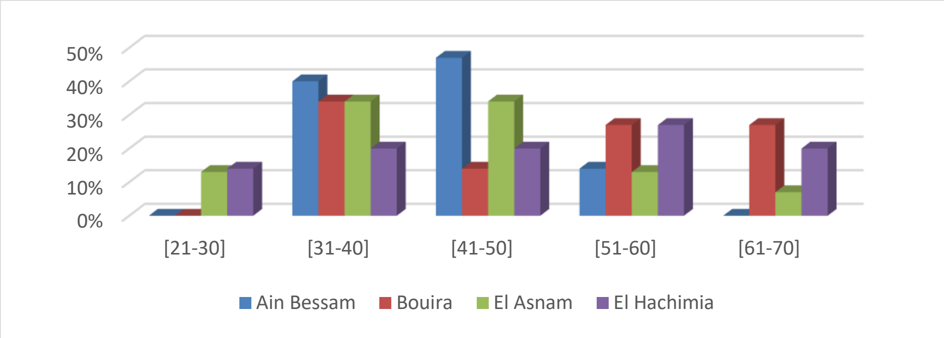

Figure 1 Age of farmers surveyed

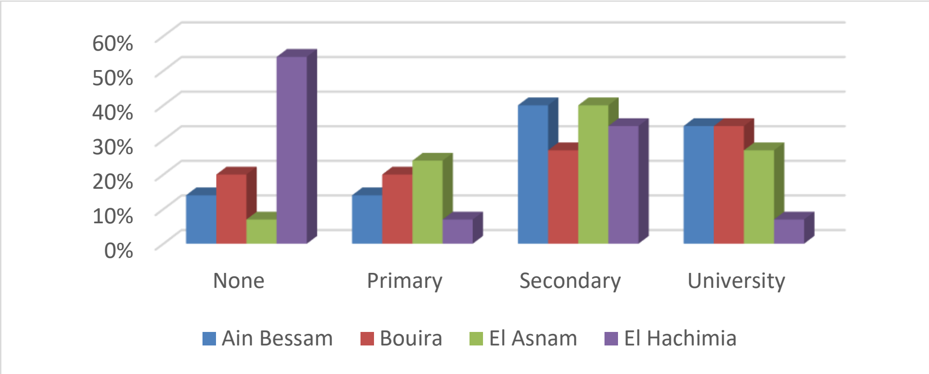

Figure 2 Level of education of farmers

Research by Soro et al. (2019) has shown that farmers' lack of education represents a major risk of poisoning both themselves and the environment, as they are unaware of the high toxicity of plant protection products.

3.2. Grown species

Durum wheat is the leading crop at all the study stations, with rates of 100% at Bouira centre, 86.67% at Ain Bessam and El Asnam, followed by common wheat and barley. By contrast, oat production at Ain Bessam did not exceed 33.33% (Fig. 4). According to the DSA, these crops are less sensitive to climatic and soil conditions and are intended for consumption or marketing.

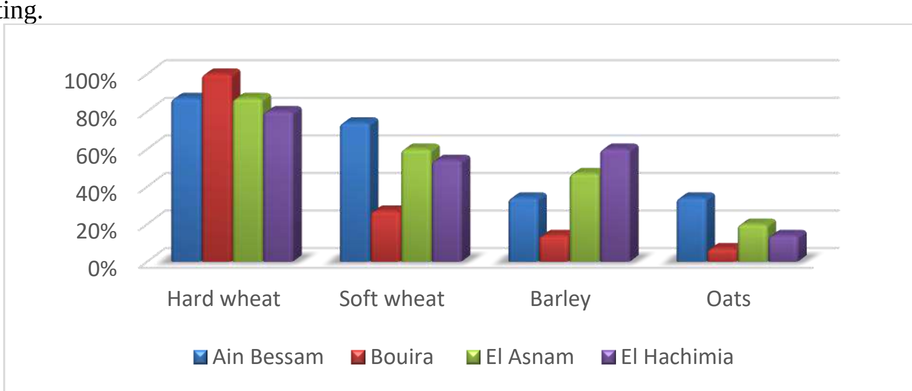

Figure 4 Species grown in the study areas

The dominance of durum wheat is a national trend; in fact, Chourghal et al. (2016) point out that this predominance reflects the overall orientation of agriculture. Similarly, since the economic changes and the end of input and equipment subsidies, durum wheat (43.61% of the area) has once again become the main product, ahead of barley and common wheat.

3.3. Use of pesticides on crops

Most cereal grower respondents regularly use pesticides to prevent and combat attacks by natural enemies. The use rates were 86.67% in El Asnam, 73.33% and 66.67% in Ain Bessam in central Bouira, respectively (Fig. 5 and 6). In El Asnam, all the farms have put preventive measures in place due to an outbreak of yellow rust *(Puccinia triformes)* on wheat. All the farmers interviewed opted for the liquid form of pesticides so that the plants could absorb them more easily.

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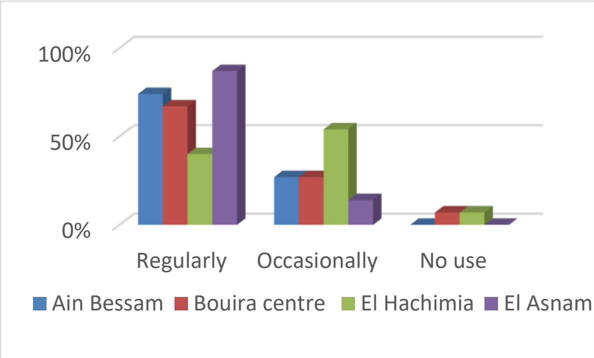


Figure 5 Frequency of pesticide use

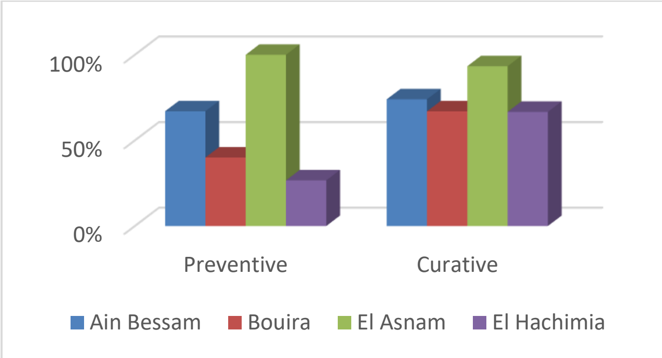


Figure 6 Treatment types.

3.4. Typology of pesticides used

Most cereal growers interviewed regularly use pesticides to prevent and combat attacks by natural enemies (Fig. 7). They acknowledge the use of various types of pesticide in different forms, sometimes mixing and alternating products to guarantee the effectiveness of the treatment methods. During our study, 24 commercial brands were identified, including 11 herbicides, seven insecticides and six fungicides (Fig. 8). All the people interviewed stated that they applied the same dose, one quintal per hectare (100 kg/ha).

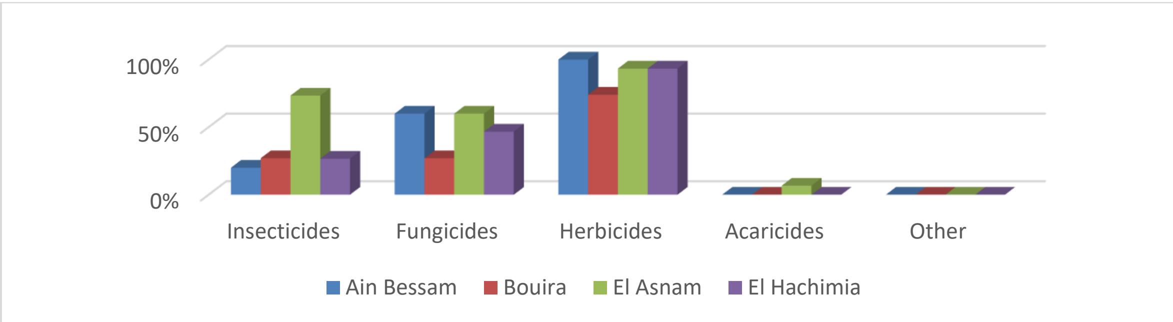
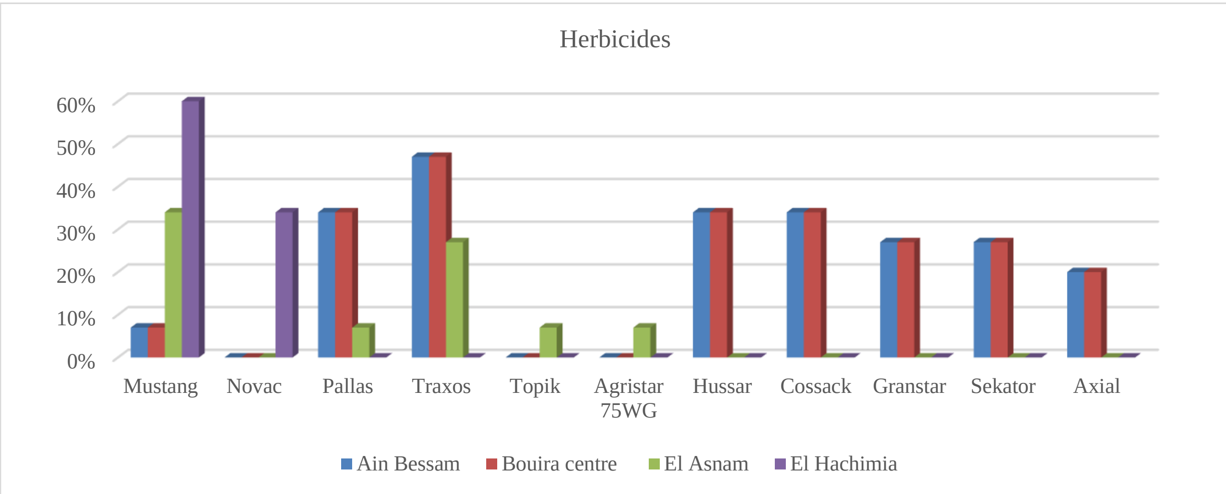


Figure 7 Typologies of pesticides used by locality



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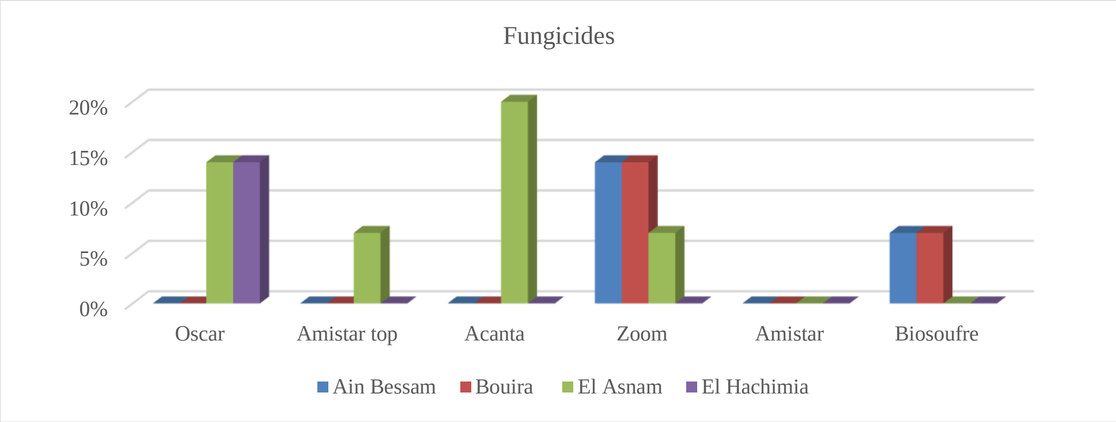

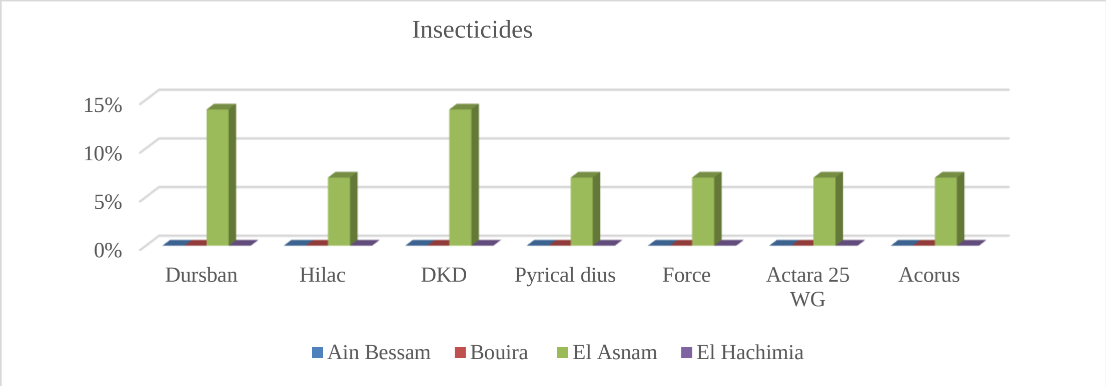

Figure 8 Types of pesticides used by cereal growers

The farmers interviewed regularly opt for pesticides, given their importance and necessity for cereal production in terms of quality and quantity. The use rates were 86.67% in El Asnam and 73.33% and 66.67% in Ain Bessam in central Bouira, respectively. The use of pesticides is a very important factor in plant protection (Ntalli & Menkissoglu-Spiroudi, 2011).

The farmers surveyed use large quantities of herbicides. This result is because natural weeding methods are no longer used, and farmers use all chemical products. The latter are more effective and easier to apply.

Fungicides are also being applied at high rates (particularly in Ain Bessam and Al Asnam, at 60%), mainly due to climatic conditions that favour the appearance of fungal diseases (late seasonal rains). Se cereal crops have also suffered an insect attack (specifically the root aphid), especially in El Asnam. The drought at the start of this year's cereal season has encouraged this pest to take hold, leading to the widespread use of insecticides. Additionally, the DSA's services confirm that farmers producing crops for seed are obliged to follow a prescribed phytosanitary protocol, and the DSA will inspect them. Failure to comply will result in losing their multiplication premiums (consumption only).

According to Guehiliz et al. (2023), in the arid region, herbicides are used very highly (88.9%). In contrast, Oultaf (2022) in the Tizi-Ouzou region observed a rate of use of 50% for fungicides and 43% for insecticides, while herbicides were used for only 4%. These results show a clear correlation between climate, the type of natural enemy and the type of pesticide applied.

It is worth noting that the lack of stringent legislation contributes to the diversity of pesticides on the market. However, governments must enforce strict regulations to minimise environmental contamination and ensure safe handling practices. The agricultural industry can adopt sustainable methods like integrated pest management (IPM) and organic farming to reduce reliance on agrochemicals. Innovations such as precision agriculture, biological pest control, nanotechnology, and artificial intelligence for early risk detection are essential (Anjaria & Vaghela, 2024).

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3.5. Pesticide selection criteria

Most cereal growers interviewed chose pesticides based on their efficacy throughout the study area, i.e. 86.67% in El Hachimia and El Asnam and 80% in Ain Bessam. The other selection criteria were used in varying proportions (Fig. 9).

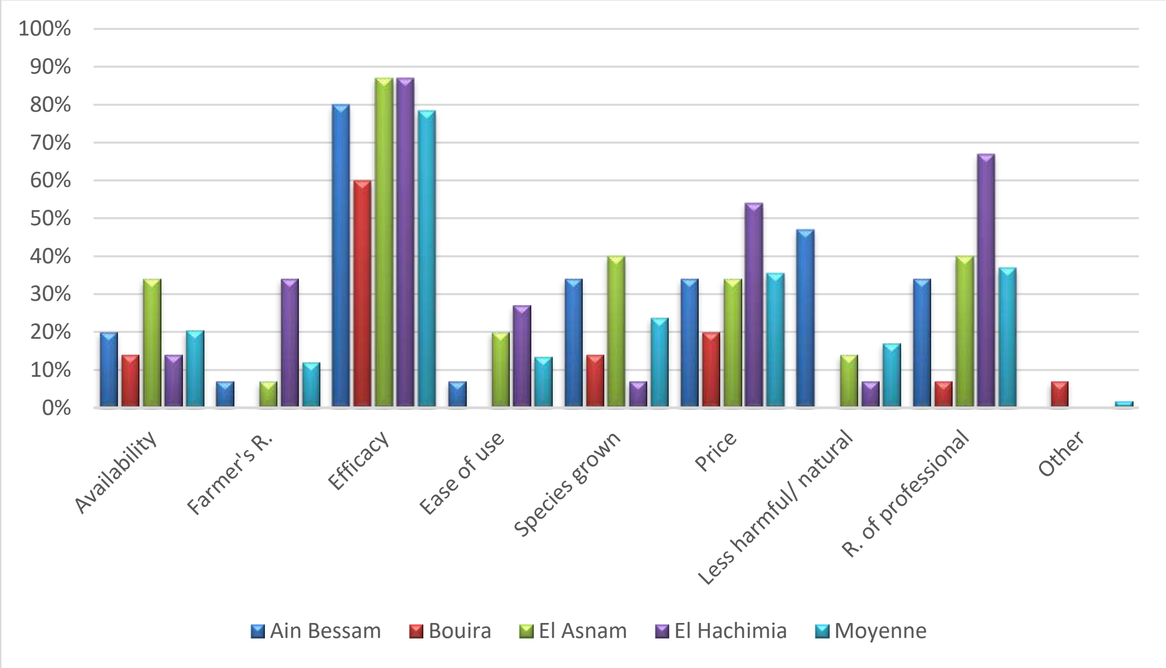

Figure 9. Criteria for selecting pesticides

3.6. Protective measures

Not all cereal growers use effective protective equipment when handling pesticides. In fact, for the complete kit, the figures recorded are low, ranging from 40% in Ain Bessam to 46.67% in El Asnam. The most commonly used means of protection are masks and gloves, with a rate of 80%. Gloves are used by 26%, while only 10% wear boots. Many farmers use other means, such as goggles (Fig.10).

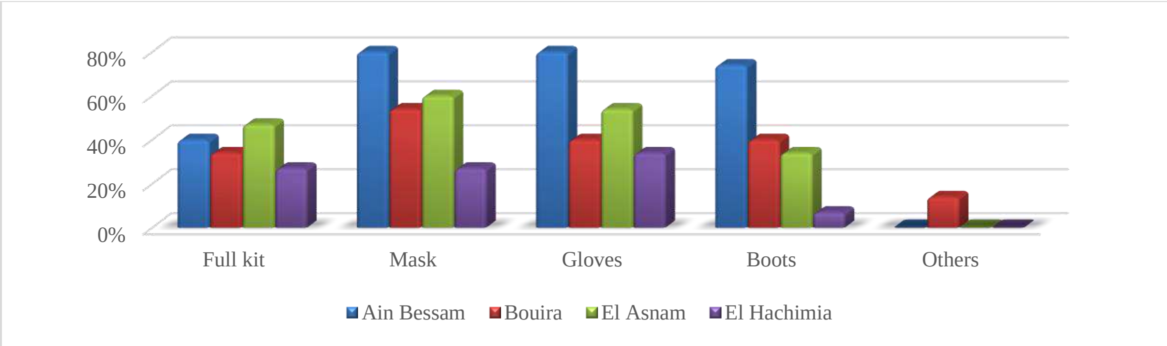

Figure 10. Protecting farmers from pesticides.

Pesticides are readily absorbed through oral, cutaneous and respiratory routes (Dayan et al., 2009). Pesticides include different substances that have different toxicities to humans (Levine, 2007).

Farmworkers and pesticide applicators face acute poisoning risks, with symptoms ranging from discomfort to severe illness or death. Chronic health effects include links to cancer, neurological disorders, and reproductive problems, raising concerns about food safety and worker well-being. Addressing agrochemical toxicity requires a multifaceted approach (Anjaria & Vaghela, 2024).

Pesticides are easily absorbed through oral, dermal, and respiratory routes (Dayan et al., 2009), posing significant risks to the health of agricultural workers and pesticide applicators. The toxic effects of these substances vary according to the type of chemical product, with some being more dangerous to human health than others (Levine, 2007). Acute exposure

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can lead to immediate poisoning, with symptoms ranging from discomfort to severe illness or even death. Even more concerning are the chronic effects associated with prolonged pesticide exposure. Studies have established a link between this exposure and diseases such as cancer, neurological disorders, reproductive issues, and other serious conditions.

These risks are not limited to workers handling pesticides but also concern the food chain, raising concerns about food safety for consumers. The widespread use of pesticides in agriculture necessitates strict adherence to safety protocols and the exploration of alternative pest management methods to reduce reliance on toxic chemical products. Ensuring the well-being of agricultural workers and the safety of food products requires a comprehensive and multifactorial approach. This includes better regulation of pesticide use, promoting protective equipment and safe handling practices, and encouraging the adoption of less harmful pest control strategies (Anjaria & Vaghela, 2024).

In cereal cultivation, where most farmers regularly use pesticides to prevent and combat natural enemies, the dangers associated with pesticide exposure become even more concerning. Farmers often mix and alternate different types of pesticides to ensure the effectiveness of treatments, but this practice increases the risks of chemical exposure for workers and the environment. Our study identified 24 commercial brands of pesticides used by these farmers, with herbicides, insecticides, and fungicides among the most commonly applied products. Despite the uniform application of pesticides at a rate of 1 quintal per hectare (100 kg/ha), it is essential to strengthen safety measures and raise awareness of the long-term health risks associated with pesticide use.

Addressing the toxicity of agrochemicals requires a balance between the need to effectively control pests and the protection of agricultural workers' health and the sustainability of agricultural ecosystems.

3.7. Waste disposal

Farmers incinerate their packaging, with the highest percentage recorded in El Hachimia (60%). In El Asnam, 40% of farmers dispose of their packaging on public landfill sites. However, 26.67% of the farmers questioned in Ain Bessam dump their waste in the countryside. Notably, 20% of farmers in Bouira dump their packaging in the ground uncontrolled, and only 6.67% of packaging is recovered by the health authorities (Fig. 11).

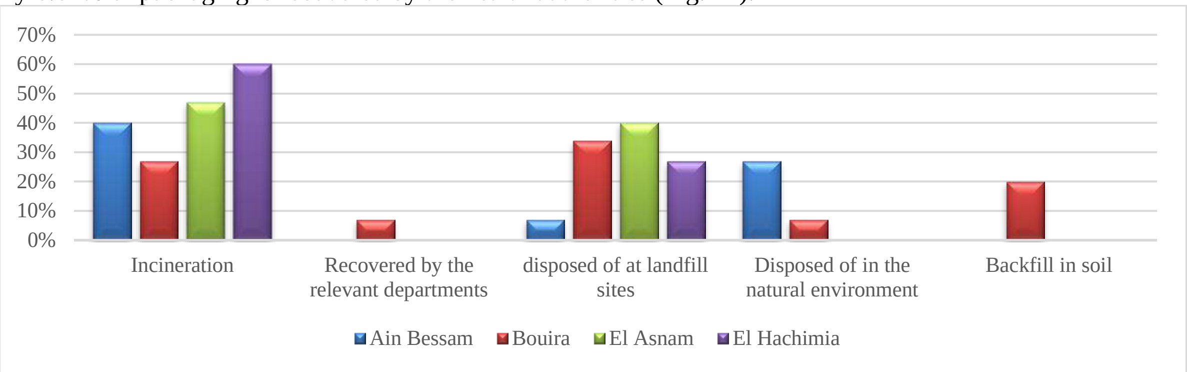

Figure 11 Packaging management

These results reveal the recklessness of most farmers who claim to have incinerated their waste or dumped it in public landfills. The most alarming finding of the survey was that in the two localities with the highest level of education (university) (Bouira and Ain Bessam), farmers either dumped their waste directly into the natural environment or poured it into the ground uncontrolled. According to Louchahi (2015), 50% of farmers abandon packaging in the fields (at the edge of the perimeters), while others throw it into rubbish dumps or watercourses (25%). Only 11.6% set fire to them, and 9% hid them. These results show that farmers' education level is not guaranteed by their actions. It should be pointed out that a recycling policy needs to be put in place to return packaging to the firms of origin.

4. Conclusion

This study sheds light on phytochemical protection practices for cereal crops in the Bouira region. We could interview cereal growers in the four agricultural zones of central Bouira, El Asnam, El Hachimia and Ain Bessam. Our survey was carried out during the 2023/2024 cereals season. The cereals grown are durum wheat, common wheat, barley and oats. Farmers use various pesticides to protect their crops and increase yields.

However, our data gives cause for concern: very few farmers are fully equipped and comply with all the protective measures. In their view, simply wearing masks and gloves when handling pesticides was more than enough protection. This attitude results from a lack of information about the real risk posed by exposure to pesticide residues.

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This study has also shown that the level of education does not guarantee farmers' actions in terms of waste management. Furthermore, our results reveal the lack of awareness of most farmers who claim to have incinerated their waste or disposed of it in public landfills and nature. This reflects farmers' ignorance and lack of awareness of the ecotoxicological risks of pesticides. These results underline the need for an increased awareness program and stricter regulations to ensure the safe and sustainable use of pesticides in cereal crops. Transitioning to more sustainable and innovative agricultural practices is essential to address modern challenges related to food security, resource management, and environmental protection.

References

Ait–Slimane-Ait-Kaki, S. (2008). *Contribution à l'étude de l'interaction génotype x milieu, pour la qualité technologiques chez le blé dur en Algérie*. Thèse de Doctorat, Université d'Annaba, Algérie.

Anjaria, P., Vaghela, S. (2024). Toxicity of agrochemicals: Impact on environment and human health. *Journal of Toxicological Studies*. 2(1). URL: https://ojs.acad-pub.com/index.php/JTS/article/view/250

Biró, K., Toldi, O. (2022). Hungarian agricultural pathways revealing climate-related challenges. *Cognitive Sustainability*. 1(4). DOI: https://doi.org/gr2bdt

Carvalho, F. P. (2017). Pesticides, environment, and food safety. *Food and energy security*. 6(2), 48–60. DOI: https://doi.org/ghp45h

Chourghal, N., Lhomme, J. P., Huard, F., Aidaoui, A. (2016). Climate change in Algeria and its impact on durum wheat. *Regional environmental change*. 16, 1623–1634. DOI: https://doi.org/f82jsj

Dayan, F. E., Cantrell, C. L., Duke, S. O. (2009). Natural products in crop protection. *Bioorganic & medicinal chemistry*. 17(12), 4022–4034. DOI: https://doi.org/dgzpm3

Djermoun, A. (2009). La production céréalière en Algérie: les principales caractéristiques. *Revue Nature & Technology*. 1(4), 45–53.

Gressel, J., Hanafi, A., Head, G., Marasas, W., Obilana, A. B., Ochanda, J., Souissi, T., Tzotzos, G. (2004). Major heretofore intractable biotic constraints to African food security that may be amenable to novel biotechnological solutions. *Crop protection*. 23(8), 661–689. DOI: https://doi.org/bq8wtt

Guehiliz, N., Boukhalfa, H. H., Deghnouche, K. (2023). Pratiques phytosanitaires des céréaliculteurs en région aride: cas de Biskra, sud-est de l'Algérie. *International Journal of Environmental Studies*. 80(3), 649–663. DOI: https://doi.org/nj8s

Lamri, N., Belayadi, A., Abbas, F. (2022). Evaluating the combination of agriculture and industry sectors in the Province of Bouira (North Algeria). *Journal of Economics and Sustainable Development*. 5(2), 1266–1287.

Levine, M. J. (2007). *Pesticides: a toxic time bomb in our midst*. Praeger Publishers Westport. URL: https://www.torrossa.com/en/resources/an/5549490

Louchahi, M. R. (2015). *Enquête sur les conditions d'utilisation des pesticides en agriculture dans la région centre de l'algérois et la perception des agriculteurs des risques associés à leur utilisation* INA. URL: http://dspace.ensa.dz:8080/xmlui/handle/123456789/1279

Mebdoua, S., Lazali, M., Ounane, S. M., Tellah, S., Nabi, F., Ounane, G. (2017). Evaluation of pesticide residues in fruits and vegetables from Algeria. *Food Additives & Contaminants: Part B*. 10(2), 91–98. DOI: https://doi.org/gphj8v

Ntalli, N. G., Menkissoglu-Spiroudi, U. (2011). Pesticides of botanical origin: a promising tool in plant protection. In: Stoytcheva, M. (ed.): *Pesticides-formulations, Effects, Fate*. InTechOpen. 1–23. DOI: https://doi.org/nj8v

Oultaf, L. (2022). *Contribution à l'etude des effets des pesticides sur l'environnement dans les regions de Boumerdès et Tizi Ouzou* Universite Mouloud MAMMERI Tizi-Ouzou.

Salim, B., & Khã, B. (2021). Water resources and food security in Algeria: Diagnosis and new strategy proposition. *African Journal of Agricultural Research*. 17(3), 414–424. DOI: https://doi.org/nj8w

Soro, G., Amao, W. S., Adjiri, A. O., Soro, N. (2019). Risques sanitaires et environnementaux liés à l'usage des produits phytosanitaires dans l'horticulture à Azaguié (Sud Côte d'Ivoire). *Journal of Applied Biosciences*. 138, 14072–14081. DOI: https://doi.org/nj8x

Soudani, N., Belhamra, M., Toumi, K. (2020). Pesticide use and risk perceptions for human health and the environment: a case study of Algerian farmers. *PONTE International Scientific Researches Journal*. 76(5). DOI: https://doi.org/nj8z

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Annexe:

Questionnaire

Assessing the phytosanitary protection of cereal crops in the Bouira region (Northern Algeria)

Series n°: ……………………………………………………………………………………...............

Date of the survey :………………………………………………………………………………

Location of municipality/ district/ province: ………………………………………………………

GPS of the survey area: …………………………………………………………………

Age of the respondents:

21-30……
31-40……
41-50……
51-60……
61-70……

Level of education/training:

- ☐ None (incomplete primary)
- ☐ Primary
- ☐ Secondary
- ☐ University

Are you the owner? ☐ yes ☐ No

Training on the application of pesticides: ☐ yes ☐ No

Awareness and dissemination day. ☐ yes ☐ No

If yes, specify the type of training……………………………………………… The organization: ……………………………………………………………………………..

The total usable agricultural area of the farm………………………………….

What are the species of cultivated cereals?

- ☐ Durum wheat
- ☐ Soft wheat
- ☐ Barley
- ☐ Oats

Do you use pesticides on your crops?

- ☐ Regularly
- ☐ Occasionally
- ☐ No

Stades phénologiquestraités

E seed coating ☐

Stage 2/3 ☐ Leaf ☐ Tillering ☐

Stem elongation ☐ Ear formation ☐

Irrigation: before application of products ☐

After application of products ☐

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Typology of products used:

Pesticides	Form			Treatment		Treatment period in the year (months)
	Liquide	Solide	Gaz	Preventive		
Insecticides						
Fungicides						
Herbicides						
Acaricides						
Other						

List the commercial names of the products used

The applied doses and the number of applications

Date	Produit Product	Parcel area	Treated area	Dose applied to the treated area (specify the unit)

How do you choose the products?

	Pesticides	Fertilizers
Availability		
Recommendation by a farmer		
Effectiveness		
Ease of use		
According to the cultivated species		
Price		
Lower toxicity to nature		
Recommendation by a professional		
Other		

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What protective measures are used when handling the products?

Complete kit	
Mask	
Gloves	
Boots	
Other	

Where do you dispose of the packaging of the products used?

Other observations :

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Radial Flux In-Wheel-Motors for Vehicle Electrification

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Abstract

In-wheel motors (IWMs) have emerged as a promising technology for vehicle electrification, offering enhanced efficiency, compactness, and design flexibility compared to traditional onboard motors. The independent and direct drive capability of IWMs allows for the advanced application and integration of a wide range of chassis active safety systems, including anti-lock braking systems (ABS), traction control systems (TCS), electronic stability control (ESC), and torque vectoring (TV). IWM manufacturers utilise toroidal motor stators for IWM electric vehicle applications where axial length minimisation is essential. An outer rotor topology with radial flux Neodymium permanent magnets allows for hosting a higher number of pole-pairs on the rotor circumference enables accommodation of a higher number of pole pairs on the rotor circumference, significantly enhancing the power and torque densities compared to traditional cylindrical motors. Inspired by early conceptual IWMs introduced by pioneering automotive and tyre manufacturers, major automotive companies today have developed unique IWM designs, each with distinguishing features. The Protean IWM stands out for its high torque density, high efficiency, fault tolerance, direct drive, and improved packaging, making it an optimal choice for a propeller. This paper explores the state-of-the-art radial flux IWMs tailored specifically for electric vehicle (EV) applications. The unique features of the Protean IWM are examined in more detail due to its potential as a propeller suitable for both retrofitting traditional vehicles with minimal tear-out and for new electrified vehicles. Finally, a comparison of the features of various IWMs is conducted, highlighting the unique strengths of each system.

Keywords
In-wheel-motor, off-wheel-motor, Protean motor, radial flux, vehicle electrification.

1. Introduction

IWM drivetrains have emerged as cutting-edge technologies that have received huge interest from researchers and manufacturers in the automotive domain due to their numerous advantages. IWMs answer questions concerning the development of the next-generation EVs and provide optimal solutions that take vehicle electrification to a new horizon. Future EVs are seen to be more sustainable, energy-efficient, environmentally friendly, simple structure, compact design, lightweight, fewer elements, reduced mechanical maintenance, flexible design, wide passenger and cargo spaces, high integration, and improved dynamics and ride comfort. Furthermore, reducing emissions and energy consumption from these technological innovations encourages consumers and industries to adopt cleaner, more sustainable transportation solutions (Silva, Ross and Farias, 2009).

Traditional EVs with central propulsion systems using off-wheel motors (OWMs) are far from answering these requirements. Therefore, to meet the previous demands, IWMs should be designed precisely to have specific features such as high power and torque density, direct drive, fault-tolerant, lightweight, compact volume, and high efficiency. As a result,

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IWMs will represent a complete departure from traditional centralised propulsion systems into distributed propulsion by integrating electric motors (EMs) directly into the wheels' rim.

The adoption of IWM drivetrains eliminates the need for several mechanical and electrical parts, including transmission, drive shafts, and mechanical and electrical connections, while allowing using shorter power cables compared to OWM drivetrains, offering numerous advantages in terms of energy efficiency, interior-free space, and cost (Fraser Alexander, 2018). Furthermore, power electronics, drive control, and sensors can all be integrated into the motor body and housed inside the wheel rim, allowing for more compactness and efficient energy consumption. From a control perspective, installing the EM inside the wheel rim enables direct drive, independent and precise driving/braking torque control, and efficient traction due to optimal utilisation of road friction. Individual control of each wheel torque allows for a better drive with the capability of applying advanced active safety systems like TCS, ABS, ESC, and TV (Said Jneid and Harth, 2023c, 2023a, 2023b). The optimal torque distribution over the four wheels improves the vehicle's performance and dynamics while maintaining energy efficiency (Said Jneid, Harth and Ficzere, 2020). This way, the mechanical connections that transfer driver commands can be replaced by electrical ones, which realise a pure control system called by-wire. With by-wire control, almost all active chassis safety systems can be implemented electronically, enabling new versions (-e). Examples of –e active controls are eABS, eTCS, eESC, and eTV. Different chassis active safety systems can be integrated using shared actuators and sensors, producing a holistic chassis active safety system that reduces elements, space, and cost.

However, some considerations must be taken into account when adopting IWMs. One common concern is the impact of increased unsprung mass on driving performance, as they add extra weight and complexity to the drivetrain (Biček et al., 2015). The increased unsprung mass increases vertical vibration, impacting ride comfort and safety (Anderson and Harty, 2010; Said (Jneid, Harth and Ficzere, 2020; De Carvalho Pinheiro, Messana and Carello, 2022). Ride comfort and vibration can be improved using dynamic suspension with a vibration absorption structure, an additional spring damper, and a controllable damper (Nagaya, Wakao and Abe, 2003).

Fortunately, systems attached to the wheels, like braking system, steering, and suspension, can also be integrated with the IWMs, enabling active IWM system, which takes vehicle integration to new heights (Said Jneid, Harth and Ficzere, 2020). This holistic approach simplifies chassis and vehicle architecture, enhances handling and ride comfort by minimising unsprung mass, improves chassis active control and integration, and maintains vehicle safety. Nevertheless, the last generation of IWM can provide high performance and comfortable riding with no unsprung mass degradation, as the case for the Michelin concept, Bridgestone dynamic-damping IWM drive system, and the advanced Protean 360^{+} electric-drive corner module (Hag, 2011; US Equal Employment Opportunity Commission, 2019; Wang and Chen, 2019).

EVs that use IWMs can be either a front-wheel drive with two IWMs on the front drive axle or a rear-wheel drive with two IWMs on the rear drive axle. When all-wheel-drive is required, four IWMs are fitted, enabling maximum performance and control. Figure 1 shows the different drivetrain topologies when using IWMs (Said Jneid, Harth and Ficzere, 2020). EVs equipped with IWMs have several advantages in terms of control and safety, efficiency, and packaging:

- Changeable drivetrain layout of front-wheel drive, rear-wheel drive, and four-wheel-drive
- EMs are connected directly to the wheels and aligned with the drive axle
- Minimum mechanical losses
- High efficiency
- High level of control integration between different active safety systems, e.g., active steering, TCS, ABS, ESC, and TV

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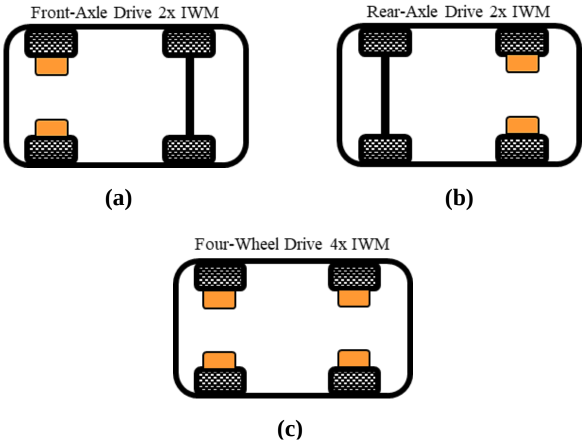

Figure 1: Different drivetrain topologies with IWMs (a): front-wheel-drive with two-IWM, (b): rear-wheel-drive with two-IWM, (c): all-wheel-drive with four-IWM, (Said Jneid, Harth and Ficzere, 2020).

To highlight the design changes in vehicle drivetrain structure when IWMs are used, Figure 2 shows a traditional internal combustion engine (ICE) vehicle with a rear-wheel drivetrain retrofitted into a conventional EV with OWMs drive in Figure 3 and then transformed into an EV with "Protean" IWMs drive in Figure 4. For traditional ICE vehicles, the drivetrain system consists of conventional mechanical systems, including the engine, transmission, exhaust, driveshaft, and differential. In a conventional EV with OWMs, the engine is replaced by a central EM with an inverter and a set of batteries installed at the back, but both the transmission and the driveshaft, in addition to the differential, remain. In the case of EVs that use IWMs, all the mechanical subsystems of the powertrain are eliminated (engine, transmission, driveshaft, and differential) and replaced with direct drive IWMs connected directly to the wheels. However, the conventional suspension is the only remaining system in this type of EV.

Figure 2: Chassis and drivetrain layout of traditional rear-wheel drive vehicle (Vallance, 2011).

Figure 3: Chassis and drivetrain layout of a retrofitted electric vehicle with OWM (Vallance, 2011).

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Figure 4: Chassis and drivetrain layout of a retrofitted electric vehicle with IWM (Vallance, 2011).

As the automotive industry continues to embrace electrification and autonomous driving, IWMs play a pivotal role in shaping the future of mobility.

This paper aims to explore the state-of-the-art radial flux in-wheel motors (IWMs) designed specifically for electric vehicle (EV) applications, focusing on their unique features, such as enhanced power and torque densities, efficiency, and fault tolerance. By conducting a detailed examination of the Protean IWM and comparing various IWM systems, this study provides insights into how these innovative technologies offer optimal solutions for advancing vehicle electrification and transforming future EV design.

The remainder of the paper is structured as follows. Sec. 2 provides the history of IWMs, Sec. 3 highlights the requirements of IWMs as propulsion systems, Sec. 4 introduces the conceptual IWMs early models, Sec. 5 explores the state-of-the-art radial flux IWMs for vehicle electrification focusing on the design features and advantages of Protean IWM, its work concept, and its potential for fault tolerance, Sec. 6 provides a comparative summary of the state-of-the-art radial flux IWMs discussed in section Sec. 5, at the same time, Sec. 7 concludes the work.

2. History of In-Wheel-Motors

As EVs were introduced before the ICE vehicles, the concept of IWMs was also introduced before OWMs as a propeller system with a first patent dating back to the first hub motor that used a brushed DC motor with a planetary gear in 1884. Next, in 1990, The idea was integrated into the Lohner-Porsche EV, featuring a pair of IWMs that propelled the vehicle to speeds above 56 km/h (Watts et al., 2010). Later, Volvo introduced the autonomous corner module (ACM) in 1998 (Rajaie, 2016). In the summer of 2003, Bridgestone unveiled its dynamic-damping IWM drive, showcasing the potential for improved handling and efficiency by mounting the EM on a specifically designed suspension system, all of which are integrated within the wheel hub. This model represented a significant leap forward in integrating propulsion systems into the vehicle chassis. Inspired by the innovations of its predecessors, Michelin introduced its active wheel system in 2004, after almost eight years of research and development in 1996 (Michelin, 2008). Michelin Active Wheel was a highly integrated propulsion and drivetrain system with active suspension.

The introduction of the Siemens VDO eCorner in 2006 marked a milestone in developing IWM technology, offering a comprehensive solution for vehicle electrification by integrating EM, brakes, and suspension components into a single module (Gerling, Dajaku and Lange, 2007). Next, the robot wheel-5 was developed at the MIT Media Lab and unveiled in 2007, showcasing active suspension and a broad steering angle capability (Schmitt, 2007). However, the concept of IWMs has endured over the past two decades and has undergone significant evolution as a requirement of the widespread adoption of electric vehicles. Today, several automotive manufacturers and research institutions are actively developing IWMs, working on innovating and producing highly efficient IWMs that address the challenges and integration requirements posed by future EV development. Despite this, each company produces a unique IWM that is distinguished from others by motor type used, performance capacity, level of integration, and potential applications.

3. Requirements of In-Wheel-Motors as Propulsion System

Various types of motors can function as in-wheel motors, such as permanent magnet synchronous motors (PMSMs), switched reluctance motors (SRM), synchronous reluctance motors (SynRM), and induction motors (IM) (Yu et al>, 2023). Because of their higher energy density, PMSMs are the most commonly chosen option nowadays. However, the selection of the IWM for EV applications must fulfil several requirements, including:

- High volumetric torque density

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- High instant and continuous torque
- High torque at low-speed range for start-up and uphill working conditions
- Low inertia and rapid response
- Lightweight for minimising unsprung mass and rotational mass
- Low cogging torque and torque ripple
- High efficiency in both constant torque and constant power regions
- Robust and fault-tolerant, capable of withstanding demanding and challenging operating conditions
- High endurance
- Compact design with a short axial length

4. Conceptual In-Wheel-Motor Models

Major automotive and tyre manufacturers have developed various IWM models along with research centres such as Volvo, Michelin, Bridgestone, Siemens VDO, and MIT. Michelin and Bridgestone have introduced active wheels by embedding the suspension and the IWM within the wheel rim. The Volvo autonomous corner module concept is designed with independent, active steering and active suspension functions through additional actuators. Further, a specialised IWM with collapsible links was suggested for a foldable chassis designed for smart-connected cars. The MIT robot-wheel-5 concept is a good example of a steer-by-wire (SBW) system. Siemens e-Corner system represents an advanced model integrating the IWM, active suspension, independent steering, and electronic wedge brakes, providing a comprehensive example of a fully chassis-by-wire (CBW) IWM. The following subsections thoroughly examine the key concepts underlying IWMs, their design, and application.

4.1. Volvo Autonomous Corner Module

The Volvo Autonomous Corner Module (ACM), illustrated in Figure 5, is a Volvo innovation developing since 1998 (Rajaie, 2016). This system incorporates an IWM, an electro-mechanical braking system, an active suspension, and active steering with the capability to adjust the wheel camber angle. The IWM power is within the range of 10-15 kW, resulting in a total power of 40-60 kW for all four wheels sufficient to propel a sports car weighing 1000 kg (Kałuża and Kornaszewski, 2017). Electric braking with energy recovery to the batteries is possible by operating the motor in generator mode. In instances of heavy braking, the electro-mechanical brake is activated to support the EM (Hag, 2011). ACM was first introduced on the Volvo ReCharge C30 hybrid car with four ACM on all wheels (Vallance, 2011).

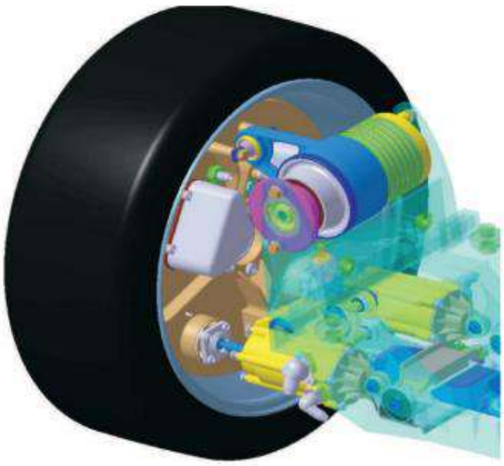

Figure 5: Schematic diagram of Volvo's Autonomous Corner Module, (Jonasson, Zetterström and Stensson Trigell, 2006).

4.2. Michelin Active Wheel

Michelin has effectively developed the Michelin active wheel (MAW) system, as shown in Figure 6, since 1996, specifically designed for EV applications (Li and Qian, 2012). All essential propulsion, braking, steering, and suspension components are integrated (Yu, Evangelou and Dini, 2023). MAW incorporates two EMs, one functioning as an IWM propeller while the other operates the active suspension. This system was first introduced in 2004 on a HY-Light vehicle with hydrogen fuel cells as its primary energy source. Subsequently, the Michelin Wheel system was applied to the modified Heuliez Will vehicle, based on the Opel Agila model, which saw faster market penetration than the HY-Light vehicle. The

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Opel vehicle incorporated two Michelin wheel drive systems cooled by water, mounted on the front drive axle, generating a total power of 30 kW, and each integrated system weighing 42 kg (Hooper, 2011).

Although wheel corner modules (WCM) systems are designed to function as an integrated direct-drive system without the need for transmission, gearboxes, or shafts, the Michelin active wheel incorporates an internal gearbox to multiply wheel torque, making it suitable for low-speed and high-torque applications. The system functions as regenerative braking when the vehicle decelerates at a low rate within motor power capacity; otherwise, friction brakes are activated to provide additional torque during hard braking conditions. The active suspension system that MAW is equipped with isolates wide-range vibrations arising from road pumps (Jandura, Břoušek and Bukvic, 2015). Furthermore, this system is designed with a wheel steering system based on a traditional steering linkage, allowing integration with either a traditional steering system or the advanced electrically operated system mounted on the vehicle chassis. However, due to concerns over the unacceptable increase in weight, space requirements within the wheel, and associated economic costs, the project was halted in 2014.

Figure 6: Michelin Active Wheel, (Jandura, Břoušek and Bukvic, 2015).

4.3. Bridgestone Dynamic-Damping In-Wheel-Motor Drive System

The collaboration between Bridgestone Corporation, Kayaba Industry, and Akebono Brake has yielded the development of the Bridgestone dynamic-damping IWM drive shown in Figure 7 (Rajaie, 2016). This innovative IWM system was first introduced in 2003. They are addressing challenges related to performance and ride comfort arising from the increased wheel mass of IWMs. Bridgestone has devised a unique suspension system tailored for their motor. In this novel approach, the EM is mounted on a special suspension, distinct from the main suspension, to mitigate the vibration resulting from the vehicle's additional unsprung mass.

Consequently, the vibrations from the motor and those from the road effectively cancel each other, improving the road-holding performance. The company asserts that applying this motor-specific suspension system results in an enhanced level of road hold and ride comfort. The transmission of motor torque to the wheels is facilitated through a flexible system featuring three disc-like hollow plates with guides. This coupling mechanism allows for a relative vertical movement of 50mm between the rotor and the wheel. Furthermore, the Bridgestone IWM system supports regenerative braking. When the electric torque proves inadequate to bring the vehicle to a stop, the electro-mechanical friction braking system intervenes, providing the torque required by the driver. An analytical study was conducted at Bridgestone to compare the road-holding performance (road surface-tyre contact force fluctuation) and the ride comfort (vertical acceleration). The study covers three EVs equipped with Bridgestone IWM drive, conventional IWM, and single OWM. Results showed improved road-holding performance and ride comfort of the EV with Bridgestone IWM drive compared to the other two EVs.

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Figure 7: Bridgestone Dynamic-Damping In-Wheel Motor Drive System (Omar and Özkan, 2015).

4.4. Siemens VDO eCorner

The Siemens VDO eCorner system depicted in Figure 8 is an advanced drive system incorporating an IWM, an active suspension, and an electronic wedge brake (EWB) system (Gerling, Dajaku and Lange, 2007). The IWM is designed with an outer rotor suitable for direct drive, enabling cohesive integration between the motor rotor and wheel (Kałuża and Kornaszewski, 2017). Additionally, this system can function in regenerative braking mode, directing recaptured energy back to the battery pack to bring the vehicle to a halt (Jonasson, Zetterström and Stensson Trigell, 2006).

In hard braking scenarios or when the EM falls short of meeting the required braking torque, EWB intervenes to top up the braking torque deficiency (Jonasson and Wallmark, 2008). EWB operates based on a self-energising concept capable of multiplying minimised actuation force from the actuator into a massive braking force (Said Jneid and Harth, 2023a). EWB represent a brake-by-wire (BBW) system comprised of an electric actuator, a precisely designed brake wedge, friction pads, and a disc brake calliper (Siemens VDO, 2006).

Figure 8: Siemens VDO eCorner, wheel rim (1); wheel hub motor (2); electronic wedge brake (3); suspension (4); electronic steering (5). Source: Siemens VDO Automotive AG, (Gerling, Dajaku and Lange, 2007)

4.5. MIT Media Lab Robot Wheel-5

A team of researchers at the MIT Media Lab have developed several models of spoke robot wheels (RWs), with the latest model being RW-5, as illustrated in Figure 9. The main aim of this design was to minimise the unsprung mass as much as possible by reducing the number of components to a minimum (Wang and Chen, 2019). This system can operate independently; hence, it is called the robot wheel. The EM used within this wheel is a brushless three-phase motor with 12 permanent magnet poles and an outer rotor. The braking system, coupled with regenerative braking to recharge the battery

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pack, is also available and capable of meeting demands under various braking conditions. Therefore, this system is not equipped with an additional friction brake.

In comparison to other systems, the RW-5 model also features an active suspension and active steering system (Hag, 2011). The distinctive feature of this system is the wide wheel steering angle of up to 150o. A vehicle equipped with RW-5 at each wheel can be steered in five different modes: front-wheel steering at ±30o similar to traditional systems, four-wheel parallel steering, four-wheel opposite steering, turning around a point with the front wheels steered inside and rear wheels steered outside, and lateral movement with a wheel steering angle of ±90o (Carvajal, 2009).

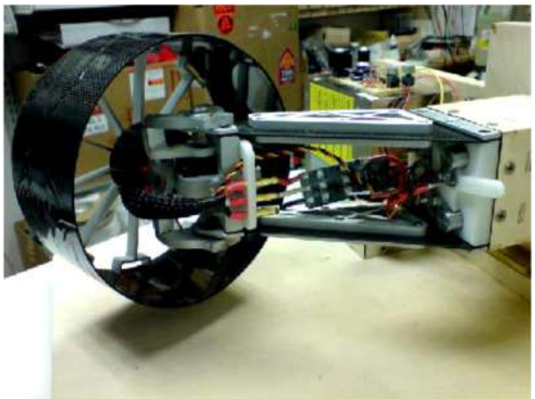

Figure 9: MIT Media Lab Robot Wheel-5 (Schmitt, 2007).

5. State-of-the-art radial Flux IWMs for Vehicle Electrification

In the previous section, the conceptual IWM Models are explored, highlighting the foundational concepts and early developments in the field of IWMs. In recent years, significant advancements have been made, driven by the urgent need for vehicle electrification and the ongoing need for more sustainable transportation solutions. This section aims to provide a detailed overview of the latest innovations, cutting-edge designs, and advancements in integrating IWMs as a compact drivetrain across various automotive industry sectors. Getting inspiration from the conceptual IWM models earlier, several companies started the development of advanced IWM units, each with a unique design, specifications, and target applications.

The following subsections present various IWM models designed specifically to meet the requirements of future EVs. Radial flux IWMs adhere to the conventional early concept of electric motors, where the magnetic lines are oriented radially between the stator and the rotor through the air gap. However, in radial flux IWMs, there are two topologies for the rotor's location, the inner and outer rotors, depending on the application area. In the EV domain with direct drive, the outer rotor is preferred as it has inherited high torque density due to the higher pole number. It can also be fitted adequately on the wheel rim, providing more space inside the wheel.

Nevertheless, the inner rotor is preferred for EVs with a central drivetrain using OWMs. Radial flux IWMs can employ PMSM, SRM, SynRM, or induction motors (IM) (Deepak et al., 2023). However, PMSM is the optimal choice for EV applications due to its high torque density from using Neodymium permanent magnets. Various manufacturers develop several radial flux IWMs, each offering unique features and capabilities tailored to meet specific application requirements.

5.1. Magnet-Motor IWM Drive Unit

Magnet-Motor (MM) produced high power, high torque in-hub-motor M70 for automotive applications, as shown in Figure 10. Its design features compactness, allowing for the integration of a friction brake or even a gearbox when torque multiplication is required. The motor is designed with an inner rotor and water-cooling intended for applications that require direct drive and high torque, such as directly driven wheels, hybrid EVs, compact military fleets, agricultural machinery, and industrial systems with high torque demand. A single or dual M70 unit can prove sufficient for normal performance.

However, high-performance vehicles can be equipped with four M70 units, providing an extreme performance suitable for various working conditions. The M70 is built for tough tasks. Operating at a peak power of 100 kW at 750V, it delivers a maximum torque of 1050 Nm and at a continuous power of 50 kW, it boasts a continuous of 500 Nm utilising a water/glycol cooling system. The motor has a medium-rated speed of 2200 RPM, fitting direct drive EV applications, eliminating the need for a gearbox to adjust torque or speed. Designed at a high-rated voltage of 750V (maximum 800V), it allows for

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minimised volumetric size and reduced copper cross-section. The reduced total weight is only 34 kg, making it compact and lightweight for easy integration into various vehicle designs. Additionally, the M70 boasts a shock resistance of 50g, ensuring durability in challenging environments (Magnet-Motor).

Figure 10: Magnet-Motor M70 radial flux IWM (Magnet-Motor).

5.2. GEM-Motors IWM Drive Unit

GEM Motors introduced RF-IWM with concentrated winding and inner rotor at a wide power range from 1 kW to 15 kW. Several generations with different specifications have been introduced, including G0, G1.1, G1.3, G2.4, G2.6, and recently G3. The G3 electric motor, shown in Figure 11, is a synchronous multi-phase motor tailored for various applications. It is well-suited for EVs with two to four-wheels and robotic applications, thanks to its modular mounting options and availability in various speed ranges. Potential applications include personal cars, light cargo vehicles, commercial vehicles, automated vehicles, farm robots, and small/light vehicles. Operating within a voltage range of 48 to 70 V, this motor delivers a peak/continuous power of 30/15 kW, max torque of 500 Nm and a speed of 1000 RPM with relatively high efficiency of up to 91% with a. It utilises permanent magnets and has an integrated controller for seamless operation (Deepak et al., 2023).

Featuring field-oriented control (FOC), the motor incorporates a regenerative braking system and four-quadrant mode operation, facilitating efficient energy usage. It offers compatibility with controller area network (CAN) 2.0 or analogue signal interfaces, enabling remote monitoring and control. Additionally, it has an ingress protection of IP67, ensuring resistance against various environmental contaminants such as salt, water, dust, acid, and alkali. G3 is available in a single/double-sided-mount configuration. The motor compact package measures 330x131 mm, making it suitable for diverse installation requirements (Products – GEM Motors | In-wheel motors and electric drive solutions, 2024).

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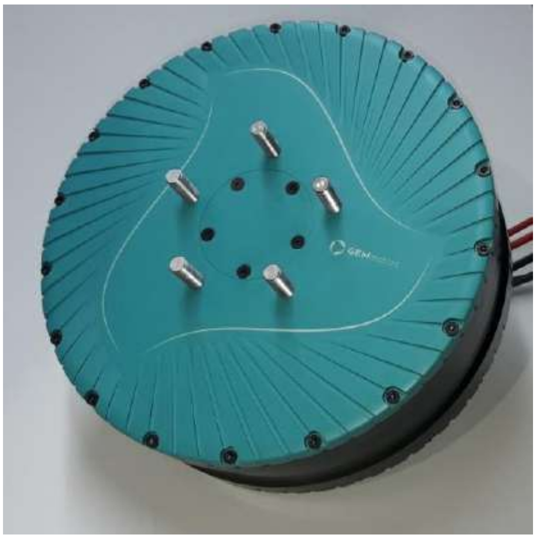

Figure 11: GEM-Motors G3 radial flux IWM (Products – GEM Motors | In-wheel motors and electric drive solutions, 2024).

5.3. Elaphe IWM Drive Unit

Elaphe designs a series of high-performance radial flux IWMs suitable for various EV applications. Elaphe IWMs are designed as a direct drive with a concentrated winding configuration and an outer rotor, making them suitable for vehicle electrification and retrofitting. The Elaphe L1500 shown in Figure 12 has a peak power of over 200 kW, a maximum/continuous torque exceeding 2000/1000 Nm, and max speeds of up to 3000 RPM, making it an optimal option for heavy-duty tasks. It ensures optimal energy utilisation with a remarkable motor efficiency exceeding 97 % and system efficiency of up to 95%. Active parts have a specific torque of up to 100 Nm/kg and volumetric torque above 500 Nm/L, demonstrating exceptional power-to-weight and power-to-volume ratios, making them a compact and efficient choice for wide-range EV applications. Its compatibility with rim sizes ranging from 16 to 23 inches allows for versatile integration into various vehicle designs. The total unit mass ranges from 25 to 65 kg depending on the rim size, ensuring lightweight and minimum added unsprung mass compared with other IWM units at the same size, ensuring minimal impact on overall vehicle weight (Technology - Elaphe, 2024).

Figure 12: Elaphe L1500 radial flux IWM (Gallery - Elaphe, 2024).

5.4. PWM Dynamics IWM Drive Unit

PWM Dynamics produces the XR IWMs series, representing a significant advancement in electric motor technology. XR IWMs are designed based on radial flux PMSM topology with an outer rotor configuration suitable for EV applications with direct drive. Outer rotor configuration ensures that motor torque is delivered directly to the wheel, maximising its geometric advantage for enhanced efficiency and power output. Furthermore, the XR series benefits from water cooling, enabling efficient heat dissipation even under demanding operating conditions. Its key feature is the ultra-flat compact pancake design,

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allowing for seamless integration into various vehicle architectures. The high slot fill achieved by using concentrated winding on each stator tooth also results in maximum torque density, further enhancing motor performance and shortening its axial length.

PWM Dynamics introduced a wide range of IWMs with various specifications that fit various applications. The list includes XR20-09, XR20-09 WC, XR25-05, XR15-03, XR32-13, XR32-11, XR15-05, XR15-W, XR15-06, XR44-16 WC, and XR32-13 WC. The latest XR32-13 WC motor shown in Figure 13 is a notable iteration within the XR series and shows impressive performance tailored for diverse applications. With a peak power/continuous of 120/62 kW and a current rating of 322Arms, it offers robust performance capabilities to meet various torque and power requirements, delivering max/continuous torque of 577/300 Nm. Operating at a speed of 2000 RPM at a DC link voltage of 100V ensures compatible vehicle speed without needing a speed reducer. The water-cooled motor weighs only 32 kg, making it a versatile solution for IWM EV applications (XR32-13 WC - PMW, 2024).

Figure 13: PWM Dynamics XR32-13 WC radial flux IWM, (XR32-13 WC - PMW, 2024).

5.5. Protean IWM Drive Unit

Protean Electric reshaped the IWM paradigm by introducing an advanced IWM drive distinct from the field counterparts, as depicted in Figure 14. The company ingeniously changed the element position of its drive unit. Protean adopts the "inside-out" approach, where the stator is moved inside while the rotor is moved outside the motor (Fraser and Whitehead, 2012). This way not only multiplies the motor torque but also brings a new level of motor integration within the wheel assembly. This configuration creates enough space where the power electronics can be embedded into the stator body and share the water cooling system (Fraser Alexander, 2018).

Furthermore, the friction braking with the brake disc is moved from the inner wheel to the outer side, improving the friction heat transfer to the environment (Perovic, 2012; Whitehead, 2012). The stator is divided into eight sub-motors, providing a high fault tolerance that is substantial for EV applications. Currently, Protean is working on a future advanced electric-drive corner module designed for next-generation high-performance mobility called Protean 360+, shown in Figure 15 (Technology - Protean : Protean, 2024 a; Technology - Protean : Protean, 2024 b).

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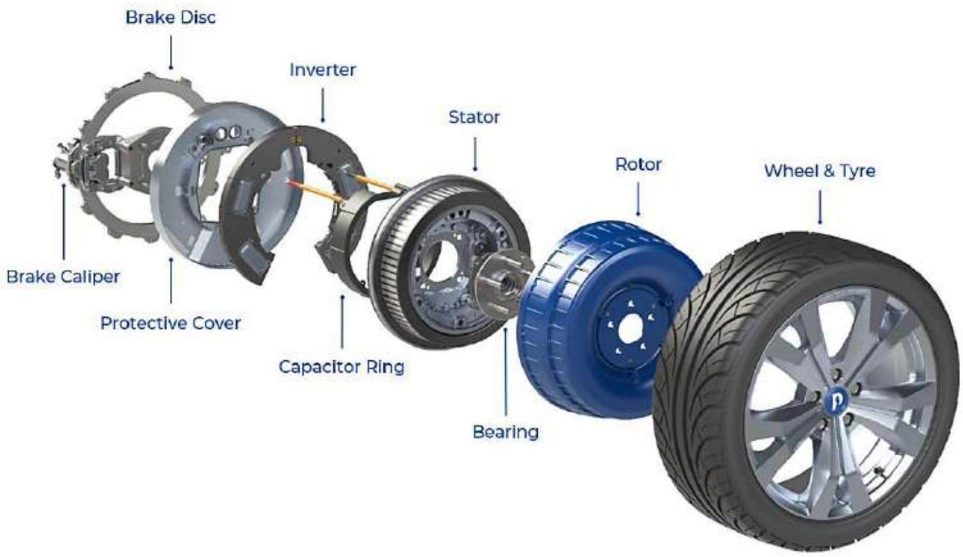

Figure 14: Protean Pd18 radial flux IWM with embedded power electronics exploded view (Technology - Protean : Protean, 2024 a).

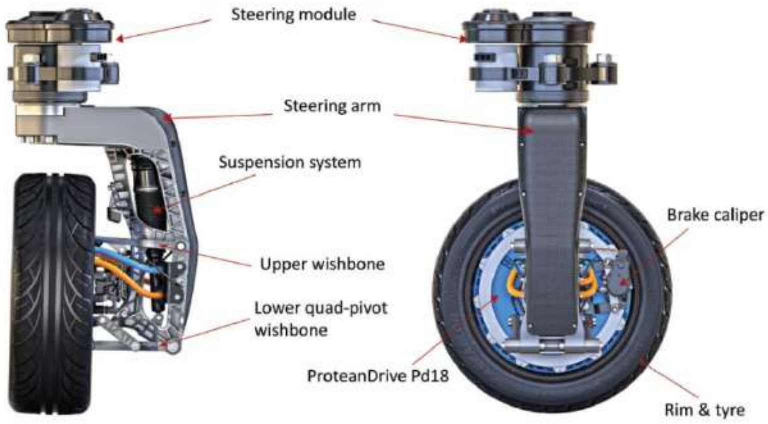

Figure 15: Protean 360+ drive corner module designed for next-generation mobility (Technology - Protean : Protean, 2024 b).

5.5.1. Components of Protean In-Wheel-Motor Unit

The Protean drive system comprises the components outlined in Figure 14, showing an exploded view of the electric motor with its drive elements, including:

- Standard wheel and tyre
- Outer rotor with surface-mounted permanent magnets fitting traditional wheel rim
- Internal stator with concentrated coils
- Drive unit with micro-inverters
- Water-cooling jacket for stator and micro-inverter heat transfer
- Outer ring brake disc
- Friction brake callipers
- Steering and suspension mountings and bearing

5.5.2. Design Features and Advantages of Protean In-Wheel-Motor

Protean IWM design is based on adopting the unique " inside-out " concept, which allows for high integration between the IWM and drives. Inside-out means the motor stator is relocated inside while the rotor is moved outside. This can be done by adopting a toroidal motor rather than a conventional cylindrical shape. This concept not only multiplies the torque density due to a larger air-gap diameter and, hence, a larger number of rotor poles but also frees up more space in the motor core where electronics can be integrated (Fraser Alexander, 2018). Although this way presents tough demands on the electronic design, it significantly cuts down on the needed cabling, where only two shielded DC cables are necessary (Aloeyi, Ali and Wang, 2022). This improves efficiency, reduces cost, and makes integration much easier while opening up more space in the vehicle, enhancing the flexibility of the in-wheel motor concept.

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The Protean IWM drive unit has the following characteristics and features:

- Direct drive, eliminating mechanical elements such as gears and shafts
- 64 PM poles for high torque density
- External hollow rotor with a radial configuration
- Sub-motors configuration (up to 8) for high fault tolerance
- Concentrated winding for more fault tolerance
- High performance in both constant torque and power regions
- High efficiency
- High reliability

5.5.3. Fault Tolerant Concept of Protean-In-Wheel-Motor

The principle of fault tolerance in machine design was initially introduced in aviation, where high energy density, operational readiness, and reliability are crucial requirements (Muenchhof, Beck and Isermann, 2009). However, this concept is also applicable and essential in the design of machines used in EVs. In the event of a malfunction, such as a failure in any wheel during driving, it might generate significant pulling or braking torque, posing the vehicle with a substantial risk. This situation can be catastrophic, particularly at high speeds. According to Protean, they generate disturbance torque during a fault condition of approximately 280Nm or higher, leading to a loss of control over the vehicle (Ifedi et al., 2011). Therefore, designing the motor with minimum faults in mind is imperative. Previous attempts to achieve a high fault-tolerance motor often focused on increasing the number of phases. Still, these efforts proved unsuccessful due to the substantial torques generated by common faults (such as a short circuit), which can be highly risky (Yepes et al., 2022).

In addition, the selection of poles and slots considers critical aspects like resistance to demagnetisation, prevention of excessive rotor temperature, and the feasibility of subdividing the motor into independent sub-motors. This subdivision is crucial for creating a highly fault-tolerant in-wheel motor system, aligning with the specified requirements outlined earlier (Wolnik, Styskala and Mlcak, 2022). To address these considerations, Protean has segmented the motor into eight independent sub-motors, adopting a configuration of 72/64 slots/poles. Each sub-motor features three phases spanning $45^{o}/360^{o}$ mechanical/electrical on the stator periphery. Mechanical displacement between subsequent phases within each sub-motor is $15^{o}/120^{o}$ mechanical/electrical. Each sub-motor boasts 9/8 slots/poles and a dedicated micro-inverter for independent control, ensuring fault tolerance and optimised performance. In the event of a malfunction in one of the eight sub-motors, a braking torque equivalent to one-eighth of the total motor torque is generated. The remaining seven healthy motors continue to deliver the required operational torque.

However, when the performance of one sub-motor is compromised, the system is expected to provide the full nominal torque, distributing the load of the affected sub-motor among the remaining sub-motors. The overload factor for each remaining sub-motor is (n-1)/n, where n represents the number of sub-motors (n=8). Consequently, each sub-motor experiences an additional load of one-seventh of the torque from the faulted sub-motor. For the vehicle, the braking torque resulting from the failure of one sub-motor does not impact its functionality, as it is still powered by a total of 31 sub-motors over the four wheels. The maximum braking torque generated when a short circuit occurs between two phases in one sub-motor is 50 Nm. This value is less than 20% of the disturbance torque, leading to a hazardous loss of control (280 Nm).

This method of dividing the motor into eight sub-motors ensures the required safety level and fault tolerance. However, in a traditional, non-divided stator, the disturbance torque would be around 400 Nm, exceeding the critical value where the vehicle loses stability (Ifedi et al., 2012). To prevent the propagation of the fault, regardless of its nature, it is crucial to minimise the impact of a fault in one sub-motor on its adjacent counterparts. This ensures that the remaining healthy motors continue to function normally. Achieving this involves designing the motor to minimise the magnetic coupling between adjacent sub-motors. Therefore, the distribution of the three-phase coils for each sub-motor ensures that only one coil out of nine shares magnetic flux with one coil from the adjacent sub-motors, as shown in Figure 16.

Nevertheless, the thermal coupling between these two coils can be high. In this case, it has been found that the reduction in the electromagnetic force of a motor adjacent to the affected motor is only 3.3%, with negligible impact (Ifedi et al., 2012). This indicates that the adjacent motor will continue to operate as expected.

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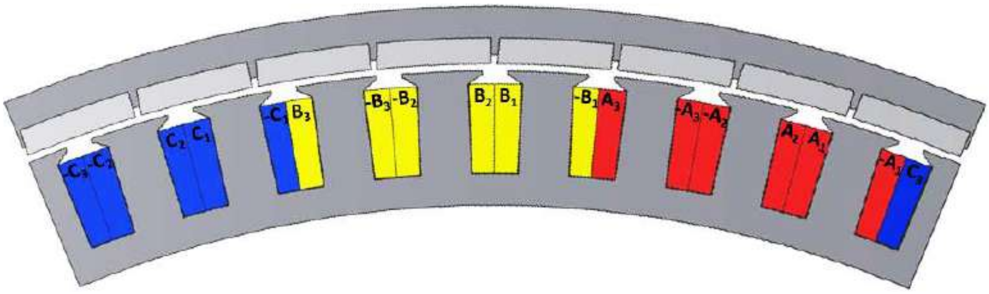

Figure 16: Three-phase winding of 9/8 slots/poles sub-motor configuration with one shared slot mitigating fault propagation (Ifedi et al., 2012).

5.5.4. Protean In-Wheel-Motor Concept and Control

Figure 17 illustrates a schematic representation of Protean sub-motors and micro-inverters, where each sub-motor with its dedicated micro-inverter forms an individual three-phase drive unit with independent control. All units are isolated but share the common DC-link connection and Controller Area Network (CAN) communication bus. Each micro-inverter is connected to the DC link through a thermal fuse to prevent fault propagation on the system level. In case of a large current flow due to a fault in one of the sub-motors or its drive system, the thermal fuse collapses, isolating the damage propagation to the other sub-units. Furthermore, the control signal from the CAN communication channel is optically isolated in each micro-inverter to prevent any fault in one micro-inverter from affecting the others.

Additionally, each micro-inverter has its own DC-Link capacitor and its drive circuits. The vehicle's main electronic control unit (ECU) receives the total torque command, divides it by eight, and delivers it to individual sub-motor micro-inverters, where each contributes one-eighth of the total torque. In case one sub-motor is faulted, the total torque is divided by seven, and in this case, each sub-motor contributes one-seventh overload.

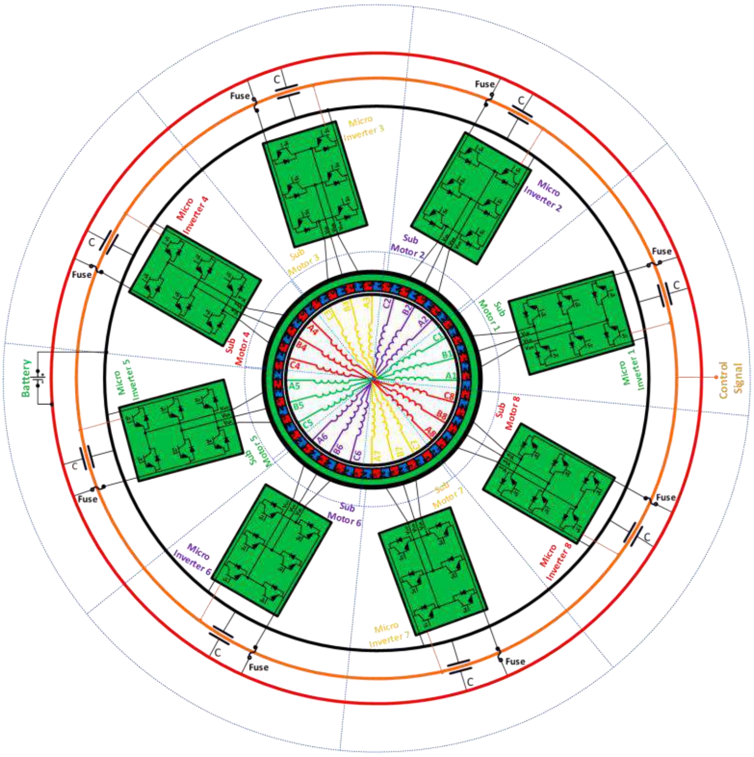

Figure 17: Individual sub-motors with dedicated micro-inverters shared common DC-link and CAN bus control.

5.5.5. Specifications and Design Features of Radial Flux IWMs

In this section, the state-of-the-art radial flux IWMs discussed in the previous section are summarised and compared in terms of peak power and torque, continuous power and torque, peak power and torque densities, peak efficiency, max speed, voltage range, mass, dimensions, drivetrain topology, motor topology, cooling system, ingress protection level, integration with other systems, and fault tolerance. Table 1 provides a comparative summary of the state-of-the-art radial flux IWMs discussed in this section.

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Table 1: Specifications and design features of state-of-the-art radial flux IWMs

IWM Unit	Magnet-Motor M70	GEMmotors G3	Elaphe L1500	PWM Dynamics XR32-13 WC	Protean Pd18	Protean Pd16
Power (Peak/ Continuous) [kW]	100/50	30/15	177/110	5.87/4.9	90/60	40/26
Torque (Peak/ Continuous) [Nm]	1050/500	550/370	1250/650	577/300	1400 (3sec)/ 1250 (18sec)/650	800/450
Max Speed [RPM]	2200	1300	3000	2000	1600	1600
DC Voltage [V]	750-800	48-100	370	100	150-430	150-430
Peak Efficiency [%]	-	System: 93	Motor: 97 System: (motor + inverter): 95	-	System (motor + inverter): 93	System (motor + inverter): 93
Mass [kg]	34	27	25	32	IWM + Inverter 36	IWM + Inverter 28
Wheel Rim Size Min [inch]	-	15	19	14	18	16
Peak Power Density [kW/kg]	2.9	1.11	7.1	0.18	2.5	1.4
Peak Torque Density [Nm/kg]	30.9	20.4	50	18	38.9	28.6
Winding Topology	-	Concentrated	Distributed	Distributed	Concentrated	Concentrated
Rotor Topology/ Poles No	Inner-Rotor	Outer-Rotor/24	Outer-Rotor/-	Outer-Rotor/-	Outer-Rotor/64	Outer-Rotor/64
Stator Topology Slots/Poles	Outer-Stator/-	Inner-Stator/18	Inner-Stator/-	Inner-Stator/-	Inner-Stator/72	Inner-Stator/72
Drivetrain Topology	Direct-Drive	Direct-Drive	Direct-Drive	Direct-Drive	Direct-Drive	Direct-Drive
Reducer / Gear-Ratio	Optional	-	-	-	-	-
Cooling System	Water/Glycol 50/50	Forced Air	Water	Water	Water/Glycol 50/50	Water/Glycol 50/50
Fault Tolerance	-	-	-	-	- Stator division into eight sub-motor - Winding electrical insulation - Winding magnetic isolation	- Stator division into eight sub-motor - Winding electrical insulation - Winding magnetic isolation
Integration level	IWM Only	IWM+ Inverter	IWM+ Brakes	IWM only	IWM + Inverter + Wheel Bearing + Brakes	IWM + Inverter + Wheel Bearing + Brakes
Ingress Protection Level	IP68	IP67	IP67 and IPX9K	-	IP69	IP69
Dimensions [mm]	Ø 437 x 134	Ø 330 x 131	Ø 232 x 142.2	Ø 324.5 x 130	Ø 433 x 125	Ø 380 x 125
Ref	(Magnet-Motor M70 Datasheet)	(Products – GEM Motors | In-wheel motors and electric drive solutions)	(Technology - Elaphe, no date; Elaphe L1500 in-wheel motor - E-Mobility Engineering, no date; Deepak et al., 2023)	(XR32-13 WC - PMW, no date; Deepak et al., 2023)	(Technology - Protean : Protean, 2024 c)	(Technology - Protean : Protea>, no date c;>Protean Electric and Zhejiang VIE Science & Technology Jointly Announce the Development of PD16 to Broaden the In-Wheel Motor Market Access - Protean : Protea>, 2024)

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5. Conclusion

Electric vehicles equipped with IWM systems demonstrate a remarkable leap in performance, control integration, and simple design compared to their traditional counterparts. This advancement is attributed to the innovative chassis-by-wire technology, complemented by additional actuators that ensure precise control over the vehicle's motion. CBW facilitates superior management of longitudinal, lateral, and vertical movements, coupled with the effective integration of advanced active safety systems. Various automotive companies have developed different IWM models with unique specifications featuring the CBW control substantial for next-generation EVs. Almost all IWM models used permanent magnet electric motors, known for their high torque density and lightweight, resulting in exceptional efficiency, particularly in the constant torque range. Protean Electric emerged as a leader in this domain and introduced a distinctive IWM design with a high level of integration, high fault tolerance, and torque density. The unique design of Protean IWM as a direct drive enables seamless integration into traditional electric vehicles without significant structural modifications. Consequently, amongst all presented IWMs, Protean IWM stands out as the optimal choice for vehicle electrification.

Acronyms

ACM	Autonomous Corner Module
ACAS	Advanced Chassis Assistance Systems
AWM	Active Wheel Module
BBW	Brake-By-Wire
CAN	Controller Area Network
CBW	Chassis-By-Wire
DYC	Direct Yaw Control
eABS	Electronic Version ABS
eESC	Electronic Version ESC
EM	Electric Motor
ESC	Electronic Stability Control
eTCS	Electronic Version TCS
eTV	Electronic Version TV
EV	Electric Vehicle
EWB	Electronic Wedge Brake
ICE	Internal Combustion Engine
IM	Induction Motor
IWM	In-Wheel-Motor
MAW	Michelin Active Wheel
OWM	Off-Wheel-Motor
PD18	Protean in-wheel-motor former model
PM	Permanent Magnet
PMSM	Permanent Magnet Synchronous Motor
RW	Robot Wheel
SBW	Steer-By-Wire
SRM	Switched Reluctance Motor
SynRM	Synchronous Reluctance Motor
TCS	Traction Control System
TV	Torque Vectoring
WCM	Wheel Corner Module

References

Aloeyi, E. F., Ali, N. and Wang, Q. (2022) 'A Review of In-Wheel Motors for Electric Vehicle Propulsion', 2022 IEEE Transportation Electrification Conference and Expo, Asia-Pacific, ITEC Asia-Pacific 2022, pp. 1–6. DOI: https://doi.org/nj78

Anderson, M. and Harty, D. (2010) 'Unsprung Mass with In-Wheel Motors - Myths and Realities', Avec, pp. 261–266. Available at URL: http://www.proteanelectric.com/wp-content/uploads/2011/12/protean-Services3.pdf

Biček, M. et al. (2015) 'Mechanical failure mode causes of in-wheel motors', Strojniski Vestnik/Journal of Mechanical Engineering, 61(1), pp. 74–85. DOI: https://doi.org/nj8b

Carvajal, M. A. (2009) 'The Design Process for Wheel-Robot Integration by'.

De Carvalho Pinheiro, H., Messana, A. and Carello, M. (2022) 'In-wheel and onboard motors in BEV: lateral and vertical performance comparison', 2022 IEEE International Conference on Environment and Electrical Engineering and 2022 IEEE Industrial and Commercial Power Systems Europe, EEEIC / I and CPS Europe 2022, pp. 1–6. DOI: https://doi.org/nj8c

Deepak, K. et al. (2023) 'In-Wheel Motor Drive Systems for Electric Vehicles: State of the Art, Challenges, and Future Trends', Energies, 16(7), pp. 1–31. DOI: https://doi.org/nj8d

Elaphe L1500 in-wheel motor - E-Mobility Engineering (no date). Available at URL: https://www.emobility-engineering.com/elaphe-l1500-in-wheel-motor/ (Accessed: 20 May 2024).

Fraser, A. and Whitehead, A. (2012) 'In-Wheel Technologies How are Brakes being Redefined ?', Protean, (November). Available at URL: http://www.proteanelectric.com/en/wp-content/uploads/2013/07/In_Wheel_Tech_Brakes_Redefined_AF_AWh_V611132012b.pdf.

https://doi.org/10.55343/CogSust.105

Fraser Alexander (2018) 'IN-WHEEL ELECTRIC MOTORS The Packaging and Integration Challenges', pp. 1–15. Available at URL: https://www.proteanelectric.com/f/2018/04/In_Wheel_Electric_Motors_AFraser_ProteanV4.pdf.

Gallery - Elaphe (no date). Available at URL: https://in-wheel.com/en/gallery-2/ (Accessed: 19 May 2024).

Gerling, D., Dajaku, G. and Lange, B. (2007) 'Electric traction for automobiles - Comparison of different wheel-hub drives', Electric Drive Transportation Association - 23rd Int. Electric Vehicle Symposium and Exposition 2007, EVS 2007 (Battery, Hybrid, Fuel Cell) Conf. Proc. - Sustainability: The Future of Transportation, 1, pp. 218–227.

Hag, J. (2011) 'Wheel Corner Modules'.

Hooper, I. (2011) 'Development of in-Wheel Motor Systems for Formula SAE Electric Vehicles', (November), p. 149.

Ifedi, C. J. et al. (2011) 'Fault tolerant in-wheel motor topologies for high performance electric vehicles', 2011 IEEE International Electric Machines and Drives Conference, IEMDC 2011, pp. 1310–1315. DOI: https://doi.org/dsngq2

Ifedi, C. J. et al. (2012) 'A high torque density, direct drive in-wheel motor for electric vehicles', IET Conference Publications, 2012(592 CP). DOI: https://doi.org/nj8f

Jandura, P., Břoušek, J. and Bukvic, M. (2015) 'The concept of a highly efficient powertrain for an electric vehicle with respect to vehicle driving dynamics', 2015 International Conference on Electrical Drives and Power Electronics, EDPE 2015 - Proceedings, (December), pp. 422–429. DOI: https://doi.org/gf64hx

Jin, X. et al. (2023) 'Improving Vibration Performance of Electric Vehicles Based on In-Wheel Motor-Active Suspension System via Robust Finite Frequency Control', IEEE Transactions on Intelligent Transportation Systems, 24(2), pp. 1631–1643. DOI: https://doi.org/nj8g

Jonasson, M. and Wallmark, O. (2008) 'Control of electric vehicles with autonomous corner modules: Implementation aspects and fault handling', International Journal of Vehicle Systems Modelling and Testing, 3(3), pp. 213–228. DOI: https://doi.org/c3fqsj

Jonasson, M., Zetterström, S. and Stensson Trigell, A. (2006) Autonomous corner modules as an enabler for new vehicle chassis solutions, FISITA World Automotive Congress.

Kałuża, S. and Kornaszewski, M. (2017) 'THE ACTIVE WHEELS SYSTEMS', pp. 1208–1210.

Li, X. and Qian, H. (2012) 'The present status and future trends of in-wheel motors for electric vehicles', Advanced Materials Research, 433–440, pp. 6943–6950. DOI: https://doi.org/fzqxfc

Magnet-Motor M70 Datasheet (no date) 'Automotive In-Hub Motor'.

Michelin (2008) 'Michelin Active Wheel Drive', Michelin, (October).

Motor, A. I. (no date) 'Automotive In-Hub Motor Torque ':

Motor, M. (no date) 'Engineering Expertise MM's products'.

Muenchhof, M., Beck, M. and Isermann, R. (2009) Fault Tolerant Actuators and Drives – Structures, Fault Detection Principles and Applications, IFAC Proceedings Volumes. IFAC. DOI: https://doi.org/bdk4t3

Nagaya, G., Wakao, Y. and Abe, A. (2003) 'Development of an in-wheel drive with advanced dynamic-damper mechanism', JSAE Review, 24(4), pp. 477–481. DOI: https://doi.org/dvhxsc

Omar, A. A. A. and Özkan, B. (2015) 'Analysis of effect of in-wheel electric motors mass on passive and active suspension systems', ARPN Journal of Engineering and Applied Sciences, 10(14), pp. 5924–5928.

Perovic, D. K. (2012) 'Making the impossible, possible-overcoming the design challenges of in wheel motors', World Electric Vehicle Journal, 5(2), pp. 514–519. DOI: https://doi.org/nj8h

Products – GEM Motors | In-wheel motors and electric drive solutions (no date). Available at: https://www.gemmotors.si/products/#gem-g-3 (Accessed: 15 May 2024).

Protean Electric and Zhejiang VIE Science & Technology Jointly Announce the Development of PD16 to Broaden the In-Wheel Motor Market Access - Protean : Protean (no date). Available at URL: https://www.proteanelectric.com/protean-electric-and-zhejiang-vie-science-technology-jointly-announce-the-development-of-pd16-to-broaden-the-in-wheel-motor-market-access/ (Accessed: 16 May 2024).

Rajaie, M. (2016) 'Design and Fabrication of a Novel Corner Wheel Module for Urban Vehicles'.

Said Jneid, M. and Harth, P. (2023a) 'Blended Regenerative Anti-Lock Braking System and Electronic Wedge Brake Coordinate Control Ensuring Maximal Energy Recovery and Stability of All-Wheel-Motor-Drive Electric Vehicles', Journal of Transportation Technologies, 13(03), pp. 465–495. DOI: https://doi.org/nj8j

https://doi.org/10.55343/CogSust.105

Said Jneid, M. and Harth, P. (2023b) 'Coordinate Torque Vectoring Control For Enhancing Handling and Stability of All-Wheel-Drive Electric Vehicles Through Wheel Slip Control Integration', in 2023 IEEE Cognitive Mobility Conf. (CogMob). Budapest, Hungary: IEEE, pp. 177–186.

Said Jneid, M. and Harth, P. (2023c) 'Integrated Braking and Traction Torque Vectoring Control Based on Vehicle Yaw Rate for Stability Improvement of All-Wheel-Drive Electric Vehicles', in 2023 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC), Venice, Italy. IEEE, pp. 1–6. DOI: https://doi.org/nj8k

Said Jneid, M., Harth, P. and Ficzere, P. (2020) 'In-Wheel-Motor Electric Vehicles And Their Associated Drivetrains', International Journal For Traffic And Transport Engineering, 10(4). DOI: https://doi.org/nj8m

Schmitt, P. (2007) 'Just Build It ! A Fully Functional Concept Vehicle Using Robotic Wheels', (1954).

Siemens VDO (2006)' technical innovations Siemens VDO drives toward the future', (October). Available at URL: https://www.sae.org/ohmag/techinnovations/10-2006/11-14-6-6.pdf.

Silva, C., Ross, M. and Farias, T. (2009) 'Evaluation of energy consumption, emissions and cost of plug-in hybrid vehicles', Energy Conversion and Management, 50(7), pp. 1635–1643. DOI: https://doi.org/bdv75c

Technology - Elaphe (no date). Available at URL: https://in-wheel.com/en/technology/#in-wheel-motor-technology (Accessed: 15 May 2024).

Technology - Protean : Protean (no date a). Available at URL: https://www.proteanelectric.com/technology/#overview (Accessed: 19 May 2024).

Technology - Protean : Protean (no date b). Available at URL: https://www.proteanelectric.com/technology/#protean360plus (Accessed: 19 May 2024).

Technology - Protean : Protean (no date c). Available at URL: https://www.proteanelectric.com/technology/#overview (Accessed: 15 May 2024).

US Equal Employment Opportunity Commission (2019)' Fact sheet Fact sheet', Nursing and Midwifery Board of Australia, 440(July), pp. 1–5.

Vallance, A. (2011) 'Advanced In-Wheel Electric Propulsion Technology', Www.Proteanelectric.Com, (April). Available at URL: http://www.proteanelectric.com/wp-content/uploads/2013/07/Protean-Electric-presentation-for-PAES.pdf.

Wang, W. and Chen, X. (2019) 'Design methodology for wheel corner module topology based on position and orientation characteristics', Mechanism and Machine Theory, 136(4800), pp. 122–140. DOI: https://doi.org/nj8n

Watts, A. et al. (2010) 'The technology and Economics of In-Wheel Motors', SAE International Journal of Passenger Cars - Electronic and Electrical Systems, 3(2), pp. 37–54. DOI: https://doi.org/dhmnng

Whitehead, A. (2012) 'Plug-in hybrids made easy - Selectable EV drive using in-wheel motors', 26th Electric Vehicle Symposium 2012, EVS 2012, 4, pp. 2361–2372.

Wolnik, T., Styskala, V. and Mlcak, T. (2022) 'Study on the selection of the number of magnetic poles and the slot-pole combinations in fractional slot PMSM motor with a high power density', Energies, 15(1). DOI: https://doi.org/nj8p

XR32-13 WC - PMW (no date). Available at: https://www.pmwdynamics.com/product/xr32-13-wc/ (Accessed: 15 May 2024).

Yepes, A. G. et al. (2022) 'A Comprehensive Survey on Fault Tolerance in Multi-phase AC Drives, Part 1: General Overview Considering Multiple Fault Types', Machines, 10(3), pp. 1–134. DOI: https://doi.org/gpx35j

Yu, M., Evangelou, S. and Dini, D. (2023) 'Advances in Active Suspension Systems for Road Vehicles', Engineering. DOI: https://doi.org/nj8q

Yu, Y. et al. (2023) 'Performance Comparison Between Permanent Magnet Synchronous Motor and Vernier Motor for In-Wheel Direct Drive', IEEE Transactions on Industrial Electronics, 70(8), pp. 7761–7772. DOI: https://doi.org/nj8r

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Comparative analysis of organisational performance using the EFQM Excellence Model: the sustainability perspective

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Abstract

Given the escalating environmental challenges, companies must recognise the impact of their activities on the planet. By acknowledging their environmental responsibilities, organisations can develop practices and foster cultures that minimise waste and enhance value while optimising costs and saving time, thereby improving productivity. Therefore, global organisations have prioritised sustainable business practices safeguarding the environment, economy, and society. Thus, this paper seeks to conduct an in-depth analysis of the sustainability strategies employed by companies within the energy sector. The study utilises the EFQM Excellence Model criteria as a wide framework to achieve a comprehensive evaluation. This model provides a structured and systematic approach to examining and guiding the sustainability practices of these organisations, ensuring a thorough and detailed assessment of their efforts and outcomes. This approach aims to identify and present best practices and common pitfalls in terms of sustainability through comparative analysis. It will highlight key aspects that each analysed organisation employs to enhance organisational performance from a sustainability perspective. This process will compile a complete collection of examples, showcasing both effective practices and common pitfalls in sustainability. These examples will function as a resource for businesses, helping them to improve their organisational performance in the field of sustainability. By learning from these case studies, organisations can adopt successful strategies and avoid common mistakes, ultimately fostering a more sustainable and efficient business environment.

Keywords
sustainability, comparative analysis, EFQM Excellence Model, organisational performance

1. Introduction

As it is known, organisational performance represents the degree of similarity between the actual outputs of an organisation compared to the targeted ones. For a long period, companies primarily focused only on financial indicators (Conțu, 2020), considering them the only relevant outputs worth considering. This approach of measuring performance using only financial indicators narrows the potential of an organisation. Also, it leads to problems such as: "*dealt only with cost components and they quantify performance only in monetary terms, but there are many non-monetarily aspects of quantification such as Quality, customer service and lead-time reduction", "financial measure to assess performance may distort strategic objectives", "modern management techniques which allows autonomous decision making to shop-floor operators cannot be explicated by traditional financial measures*" (Looy and Shafagatova, 2016). Considering these statements, it can be affirmed that analysing organisational performance only from a financial perspective is incomplete. Therefore, organisational performance is just a short-term problem or a result of the moment because long-term performance is related to three main elements:: economics, society and environment. By measuring and constantly tracking a company's impact on these elements and comparing them with the objectives set for each of these branches, organisations can have a comprehensive and real approach to organisational performance. Thereby, it can be said that "*the traditional shareholder-focused perspective, which primarily aimed at maximising financial returns for shareholders, has evolved*" (Chungyalpa, 2021). The fundamental determinants that can significantly influence the achievement of financial performance are

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disclosed; these include the satisfaction of customers and their trust, the contentment of stakeholders, the fulfilment of employees, and the positive environmental impact.

The three elements recommended for analysing organisational performance, i.e., economic, social, and environmental factors, are the pillars of the "Triple Bottom Line" concept of sustainability. Since "*sustainability represents balancing the needs of the existing generation with the needs of the future generations in order to ensure that the next generation is able to meet their own needs in the future (World Commission on Environment and Development, 1987)*" it can be extended to businesses as "*Sustainability Performance (SP) is the organisation's ability to meet existing business and its stakeholders' needs while maintaining and enhancing the natural and human resources needed for the future* (World Commission on Environment and Development, 1987), (Balcıoğlu, Çelik, & Altındağ, 2024)". The "triple bottom line" concept was invented by John Elkington in 1994 and is a framework for integrating the three pillars of sustainability: economic, social and environmental aspects (Figure 1). The figure below illustrates that this concept encompasses all financial aspects while highlighting the environmental and social elements a company must consider. It emphasises the importance of setting clear objectives to ensure comprehensive sustainability. This new approach has, as a result, "*the fact that the responsibility of the company is not only to generate economic welfare (i.e., profit), but also to care for society (e.g., people) and the environment* (i.e., the planet) (Fauzi, Svensson, & Rahman, 2010)". That is why this comparative analysis of organisational performance benchmarks best practices in sustainability within the energy sector. By showcasing these practices, the paper aims to provide insights and recommendations for other companies to adopt similar strategies, enhancing sustainability performance across the industry. Additionally, the structured approach fosters a results-oriented culture within companies, incorporating a strong focus on sustainability. All this considers the increasing attention and pressure of world organisations (i.e. European Union, United Nations, Environmental Protection Agency) and governments to transform companies into "green organisations".

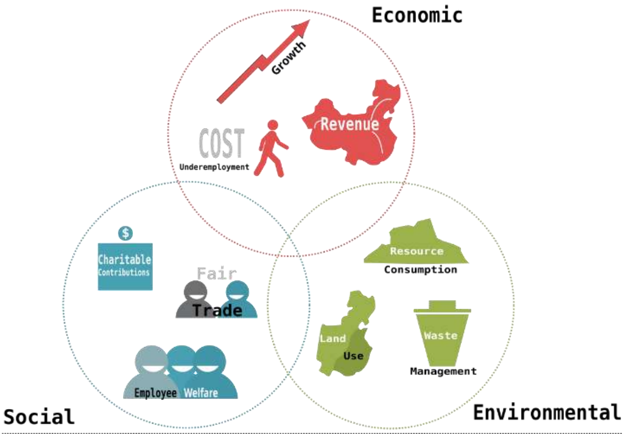

Figure 1. The three pillars of sustainability (Severin, Dijmarescu, & Caramihai, 2022)

Keeping these elements in mind, the present paper represents actual and necessary research for organisations, providing a detailed analysis of the best practices and examples of mistakes made in applying sustainability to culture and activities. The EFQM Excellence Model highlights successful strategies and common pitfalls in a comprehensive view of integrating sustainability in organisations. Through the EFQM Excellence Model criteria, it was possible to target both the external part of the organisation and its internal environment.

The EFQM Excellence Model (European Foundation for Quality Management Excellence Model) was created in 1989 and is a management framework that helps organisations navigate change and enhance performance. The model contains eight fundamental principles for organisational excellence and nine related criteria. Five of these criteria are classified as "Enablers" (leadership, people, policy and strategy, partnerships and resources, and processes), while the remaining four are categorised as "Results" (people results, customer results, societal impact results, and business results). The 'Enabler' criteria describe what an organisation does, while the 'Results' criteria reflect what an organisation achieves. 'Results' are driven by 'Enablers', and 'Enablers' are enhanced through feedback from 'Results' (Santos-Vijande and Alvarez-Gonzalez, 2007). For the present work, it is necessary to approach only the last principle from it, namely "Taking Responsibility for a sustainable future" and to be guided by its criteria ("Leadership", "Strategy", "People", "Partnership, Products and Services",

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"Customer Results", "People Results", "Society Results" and "Key Results") for the comparative analysis of the companies. The Model, recognising the diversity of methods for attaining sustainable excellence across all performance areas, is based on the principle that: "*Excellent results with respect to Performance, Customers, People and Society are achieved through Leadership driving Policy and Strategy that is delivered through People, Partnerships and Resources, and Processes* (EFQM, 2002) (Santos-Vijande & Alvarez-Gonzalez, 2007)". The EFQM Excellence Model is the most used framework in Europe for organisational quality (Eskildsen & Dahlgaard, 2000), and it is the basic model for evaluation for the European Quality Award. Therefore, in this paper, the analysis was guided by the EFQM model, focusing solely on the principle of sustainability (Figure 2) to achieve the proposed objectives.

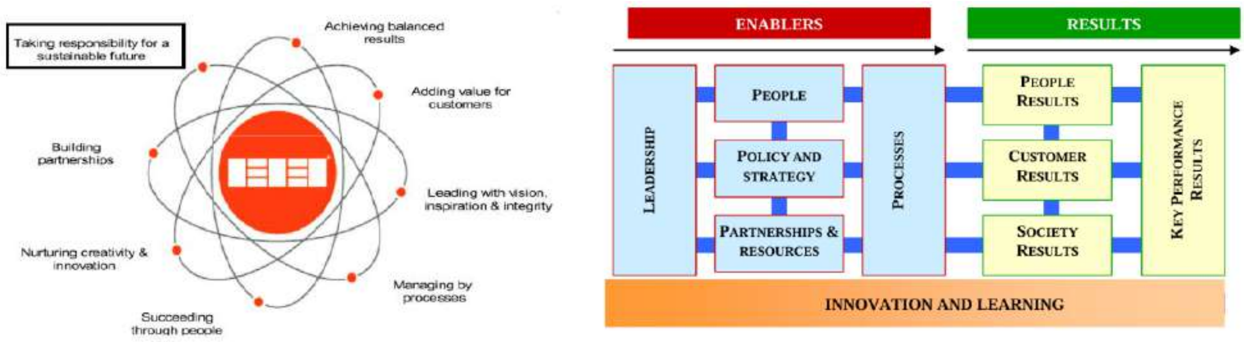

Figure 2. The "Taking responsibility for a sustainable future" principle (Olaru, Stoleriu, & Șandru, 2011) of the EFQM Excellence Model (Santos-Vijande & Alvarez-Gonzalez, 2007)

In this paper, the model facilitates the analysis of how organisations lead, plan, act, assess, and achieve sustainable performance. It identifies each company's environmental policies and strategies, including measures to reduce carbon emissions, manage natural resources, and promote renewable energy. Additionally, it examines operational performance in areas such as energy efficiency, waste management, and environmental impact. The model also highlights efforts and initiatives related to community engagement and corporate social responsibility, assessing their impact on sustainability at both local and global levels.

2. Data and methods

The analysis presented here focused on three large companies in the energy sector, which are market leaders in different areas: Siemens Energy in Europe, General Electric Power in the USA and Mitsubishi Power in Asia. By selecting three companies from different regions of the world, each with unique organisational cultures influenced by their local lifestyles, this paper will conduct a comprehensive benchmark to identify best practices in sustainability and highlight aspects that should be avoided.

Using the comparison criteria from the EFQM Excellence Model's concept of Taking Responsibility for a Sustainable Future, this analysis examines each company's sustainability practices' strengths and areas of improvement. The evaluation is based on each sub-criterion of the EFQM Excellence Model. Public Sustainability Reports from each company's website and information from the press served as sources for this analysis.

To better understand the context in which these three companies operate and their situation in the market, a brief overview of each is presented below.

- Siemens Energy is a global leader in energy business, with its headquarters in Europe. It is present in more than 90 countries, with around 99,000 employees. 16% of global electricity generation is based on their technology (Siemens, 2024);
- General Electric Power is a leading company in the energy sector, with headquarters in the USA. It boasts over 130 years of experience. It has around 75 000 employees globally, and GE's technology base helps generate "approximately 25% of the world's electricity" (GE Vernova, 2024);
- Mitsubishi Power is a leading company in the energy sector, with its headquarters in Japan. It is in over 30 countries and has approximately 18,000 employees across its global network (Mitsubishi Heavy Industries, 2023).

With this foundational information about each company now established, we can proceed with the detailed analysis of their sustainability practices. Therefore, in Table 1 below, criteria related to the chosen principle, "Taking Responsibility for a Sustainable Future", and the three companies are schematically presented. The information collected about the practices of each individual organisation is presented in Table 2, Table 3, and 4.

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Table 1. Criteria for EFQM Excellence Model and the three leading companies in the energy industry

Taking Responsibility for a sustainable future				
Criterion \ Companies		Siemens Energy *Europa*	General Electric Power *U.S.A.*	Mitsubishi Power *Asia*
1	*Leadership*	1.a. Leaders develop the Mission, Vision, Values and ethics and act as role models. 1.b. Leaders define, monitor, review and drive the improvement of the organisation's management system and performance. 1.c. Leaders engage with external stakeholders.		
2	*Strategy*	2.c. Strategy and supporting policies are developed, reviewed and updated.		
3	*People*	3.d. People communicate effectively throughout the organisation. 3.e. People are rewarded, recognised and cared for.		
4	*Partnership & Resources*	4.c. Buildings, equipment, materials and natural resources are managed in a sustainable way.		
5	*Processes, Products & Services*	5.d. Products and Services are produced, delivered and managed.		
6	*Customer Results*		-	
7	*People Results*		-	
8	*Society Results*	8.a. Perception 8.b. Performance Indicators		
9	*Key Results*		-	

Table 2. Criteria for EFQM Excellence Model regarding Siemens Energy

1.Leadership – "*Excellent organisations have leaders who shape the future and make it happen, acting as role models for its values and ethics and inspiring trust all times. They are flexible, enabling the organisation to anticipate and react in a timely manner to ensure the ongoing success of the organisation*" (Severin, 2023/2024).

1.a. Leaders develop the Mission, Vision, Values and ethics and act as role models.	
STRENGTHS	Leaders of Siemens Energy develop the organisation's goals and vision and culture through a sustainable view. Namely, they push the organisation to reduce greenhouse gas emission and produce renewable energy. They are committed to enabling decarbonisation through technology, addressing the lack of social inclusion, and creating sustainable energy solutions for the through partnerships. Leaders demonstrate and modelvalues, ethics and public responsibilities that support the culture by attending, organising and rewarding projects related to climate-neutrality, eco-efficiency, zero pollution, circular economy and zero harm. Siemens Energy Leaders set and communicate the clear direction of the organisation on sustainability by disseminating the three key areas: low- and zero- emission power generation, efficient transmission and storage of electricity and reducing CO_2 emissions from industrial processes. These three key areas are in the strategy of the Siemens Energy (Baldassarre and Finken, 2015).
AREAS FOR IMPROVEMENT (AFI)	Leaders failed to implement robust cybersecurity protocols, which led to a ransomware attack by the Cl0p group exploiting a MOVEit software vulnerability. This incident exposed vulnerabilities in their data protection strategies (SecurityWeek, 2023). The strategic vision for the wind energy sector was not effectively executed. Leadership underestimated the complexity and challenges of scaling up their wind turbine operations, leading to a disconnection between their strategic ambitions and operational capabilities (Siemens, 2024). Leaders did not effectively manage financial risks, as evidenced by the significant drop in share price following their request for government guarantees (SecurityWeek, 2023). Leaders failed to address persistent technical issues within the wind turbine division, which led to significant operational disruptions and increased costs. These unresolved issues have undermined the company's ability to deliver on its renewable energy projects effectively (Siemens, 2024).
1.b. Leaders establish, oversee, evaluate, and propel the enhancement of the organisation's management system and performance.	

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STRENGTHS	Leaders of Siemens Energy had integrated a management system for Business Area, Regional Hubs and Corporate Functions to speed up the services, to simply processes and for transparency in order to implement an ESG (environmental, social, governance) approach. Leaders develop and sustain risk and environmental management systems to improve the processes. Siemens Energy Leaders help in the design and implementation of an establishment, developing and reviewing the process of the organisational management system. Leaders ensure the minimisation of the impact on the environment through environmental management system, and they implement the approach of product stewardship by including all the environmental aspects, with the focus on climate change adaptation and resource efficiency. Leaders create the structure of the organisation in alignment with the policy and strategy according to an integrated management system covering quality (ISO 9001), environment (ISO 14001) and health and safety (ISO 45001) (Baldassarre and Finken, 2015).
AREAS FOR IMPROVEMENT (AFI)	Leaders did not manage financial risks adequately, evidenced by a significant share price drop following a request for government guarantees. This highlights shortcomings in financial planning and crisis management systems (SecurityWeek, 2023). Leaders failed to implement effective cybersecurity measures, leading to a ransomware attack by the Cl0p group exploiting a MOVEit software vulnerability. This exposed weaknesses in their data protection and risk management systems (SecurityWeek, 2023).
1.c. Leaders engage with external stakeholders.	
STRENGTHS	Leaders of Siemens Energy develop and sustain the usage of the Net Promoter Score (NPS) to evaluate and measure customer satisfaction. Leaders analyse the organisational performance in relation with to the satisfaction of customer requirements by evaluating this NPS score. Leaders conduct a materiality analysis in order to establish the Sustainable Program, engaging with selected internal and external stakeholders' groups such as customers, investors and partners. Leaders promote, support and engages in activities and collaborations with stakeholders in order to improve the sustainable improvement of the organisation and also to foster the environment and society. They make efforts to analyse, understand and meet needs and expectations of the stakeholders (Baldassarre and Finken, 2015).
AREAS FOR IMPROVEMENT (AFI)	Leaders did not fully anticipate or identify stakeholder perceptions that could lead to conflicts, which is crucial for ensuring smooth operations and maintaining a good reputation in customer projects (Siemens, 2016). Leaders communicate poorly with stakeholders, including shareholders and government entities. They may not have been as proactive or transparent as needed during times of crisis (MSN, 2024).
1.e. Leaders ensure that the organisation remains adaptable, and handles change efficiently.	
STRENGTHS	The company has partnered with The Institute of Leadership to provide its leaders and managers with development programs aimed at high performance and effective team management (The Institute of Leadership, 2023). Siemens Energy is focused on establishing the next generation of management, which includes making pivotal personnel decisions to navigate the company through transitions (Siemens, 2020). Leaders are distinguished by outstanding performance becoming a motivational engine for their employees. They always seek to exceed their potential and promote employee involvement (Siemens Energy, 2024).
AREAS FOR IMPROVEMENT (AFI)	Leaders need clear and transparent communication channels and engaging employees in the change process (Hall, 2023). The supply chain of Siemens Energy is becoming increasingly complex, with growing risks and requirements. Leaders must manage these effectively to ensure efficiency, flexibility, and customer satisfaction (Siemens, 2023).

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2.Strategy – "*Excellent organisations implement their Mission and Vision by developing a stakeholder focused strategy. Policies, plans, objectives and processes are developed and deployed to deliver the strategy*" (Severin, 2023/2024).

2.c. Strategy and supporting policies are developed, reviewed and updated.	
STRENGTHS	The Siemens Energy strategy is designed, developed and reviewed in accordance with the organisation's Mission and Vision in the direction of sustainability The Siemens Energy strategy is reaffirmed through the focus on decarbonisation and transformation of green energy. Siemens Energy's strategy balances the needs and expectations of stakeholders in the short and long term in order to be able to reach its sustainability targets Siemens Energy has identified its critical success factors through annual sustainability reports. Siemens Energy adopts robust methods to anticipate future scenarios such as the resulting climate outcomes and a detailed annual forecast for their CO_2 emission footprint of products and management strategic risks (Siemens Energy, 2023).
AREAS FOR IMPROVEMENT (AFI)	Siemens Energy strict government policies and environmental regulations can affect operations, especially as Siemens Energy is an international company operating in various jurisdictions (MBA Skool, 2023). Rapid technological changes could affect Siemens Energy's business and operating results, requiring constant innovation and adaptation (GlobalData, 2024).

3.People – "*Excellent organisations value their people and create a culture that allows the mutually beneficial achievement of organisational and personal goals. They develop the capabilities of their people and promote fairness and equality. They care for, communicate, reward and recognise, in a way that motivates people, builds commitment and enables them to use their skills and knowledge for the benefit of the organisation*" (Severin, 2023/2024).

3.d. People communicate effectively throughout the organisation.	
STRENGTHS	Siemens Energy sets the prevention and communication as the key factors for implementing a functional health and safety system. Siemens Energy uses internal communication systems/ channels such as Viva Engage for ongoing communication. Siemens Energy promotes effective and transparent reporting and communication and develop training around different topics (Siemens Energy, 2023). Siemens Energy conducts regular surveys on organisational culture and practices integrity on employees to obtain their feedback (Siemens Energy, 2023).
AREAS FOR IMPROVEMENT (AFI)	Siemens Energy faced a crisis that led to a significant loss in market value, partly due to poor communication regarding quality issues in its newest turbine models (The Guardian, 2023). Siemens Energy commented on media reports stating that order intake and revenue are expected to be lower than market expectations for fiscal year 2024, which indicates a need for better strategic communication to manage investor expectations (Siemens Energy, 2023).
3.e. People are rewarded, recognised and cared for.	
STRENGTHS	Siemens Energy promotes a global campaign for continuous improvement and self-directed learning and development Siemens Energy promotes an organisational culture of rewarding employees who excel in their work or especially help their colleagues. Siemens Energy ensure an organisational culture through which it is promoted the variety of people. Siemens Energy provides a secure and healthy work environment for their employees through the physical safety of the workplace, but also through regular trainings on EHS (environmental, health, safety). Siemens Energy invests in employees' professional growth through training programs, workshops, and educational opportunities demonstrates a commitment to their long-term success (Siemens Energy, 2023).
AREAS FOR IMPROVEMENT (AFI)	Siemens Energy should implement a system that recognises individual contributions and achievements, as it can can boost morale and productivity (Siemens Energy, n.d.). Siemens Energy should offer more opportunities for career advancement and professional growth that can serve as a reward and incentive for employees (Siemens Energy, n.d.). Siemens Energy should improve communication about how rewards are determined and distributed, which can help employees understand and appreciate the reward system (Siemens Energy, n.d.).

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4.Partenership and Resources – "*Excellent organisations plan and manage external partnerships, suppliers and internal resources in order to support strategy and policies and the effective operation of processes. They ensure that they effectively manage their environmental and societal impact*" (Severin, 2023/2024).

4.c. Buildings, equipment, materials and natural resources are managed in a sustainable way	
STRENGTHS	Siemens replaces some of their old equipment such as electric motors of exhauster, vacuum systems, air conditioners, air compressor etc. with the one more efficient in order to energy saving and to obtain less negative environmental impact. Siemens Energy actively demonstrates its commitment to reduce the negative environmental impact of their operations, while producing green energy. Siemens Energy sustains their less negative impact on sustainability by products (such as ground robots) equipped with environmental sensors that can assess air and water quality. Siemens Energy opted for helping the production of steel by electric arc furnaces instead of coal-fired furnaces. Siemens Energy implemented energy-efficient measures such as insulation, efficient HVAC systems, and LED lighting, which can result in the reduction of excessive energy consumption and greenhouse gas emissions. Siemens Energy upgraded machinery and equipment to newer, more energy-efficient models even when they are available (Siemens Energy, 2023).
AREAS FOR IMPROVEMENT (AFI)	Siemens Energy faces high energy costs, and investing in sustainability and energy efficiency is a challenge that also impacts their competitiveness (Siemens, n.d.). Siemens Energy must succeed in decarbonising energy systems along the entire value chain. Achieving this goal is challenging due to technological, financial, and regulatory hurdles (Siemens Energy, n.d.).

5. Processes, Products and Services – "*Excellent organisations design, manage and improve processes, products and services to generate increasing value for customers and other stakeholders*" (Severin, 2023/2024).

5.d. Products and Services are produced, delivered and managed.	
STRENGTHS	Through their products, Siemens Energy supports customers in their transition to a more sustainable world. Siemens Energy manages its products through their entire lifecycle, including reuse and recycling when appropriate, while considering their impact on sustainability. Siemens Energy helps in reducing negative impact on environment through their products. Siemens Energy incorporates environmental sustainability principles into product design, manufacturing processes, and supply chain management to minimise environmental impact. Siemens Energy offers training programs, workshops, and knowledge-sharing platforms to empower customers and enhance their capabilities. Siemens Energy provides personalised customer support and consulting services to address specific needs and challenges, from project planning to operation and maintenance (Siemens Energy, 2023).
AREAS FOR IMPROVEMENT (AFI)	Siemens Energy faces difficulties in aligning products with decarbonisation targets, because the value chain is complex, especially when transitioning to renewable energy sources (Siemens Energy, n.d.). Siemens Energy faces difficulties in adapting to various global regulations and standards for sustainability, because it might be resource-intensive and requires constant vigilance (Siemens Energy, n.d.).

8. Society Results – "*Excellent organisations (1) develop and agree a set of performance indicators and related outcomes to determine the successful deployment of their societal and ecological strategy and related policies, based on the needs and expectations of the relevant external stakeholders, (2) set clear targets for Key Results based on the needs and expectations of their external stakeholders, in line with their chosen strategy, (3) demonstrate positive or sustained good Society over at least 3 years, (4) clearly understand the underlying reasons and drivers of observed trends and the impact these results will have on the performance indicators and related outcomes, (5) anticipate future performance and results, (6) understand how the Key Results*" (Severin, 2023/2024).

8.a. Perception	
STRENGTHS	Siemens Energy is perceived as an expert company in the fight against corruption in the energy sector, which is confirmed by the external perceptions of stakeholders. Siemens Energy conducts surveys that show that Siemens Energy is in the top organisations that focus on efficiency as well as greenhouse emissions. Siemens Energy conducts operational surveys throughout the year that demonstrate the clear progress of NPS (Net Promoter Score – index which measures willingness of customer to recommend a company's products or services to others) score, which indicates improved customer satisfaction concerning sustainability. Based on Siemens Energy's internal surveys, they implement training strategies and develop communication ways for employees. Siemens Energy establishes ongoing communication channels with stakeholders through various means such as surveys, focus groups, interviews, forums, social media, and dedicated websites. Siemens Energy continuously evaluates and refines stakeholder engagement strategies based on feedback, lessons learned, and emerging trends (Siemens Energy, 2023).
AREAS FOR IMPROVEMENT (AFI)	There is a gap between the public perception of Siemens Energy's sustainability efforts and the actual progress the company is making. Bridging this gap is crucial for maintaining credibility and trust (Siemens Energy, n.d.).

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	The company acknowledges the need for speed in global cooperation to tackle climate change, but there is a perception that efforts are not moving quickly enough to meet global warming targets (Siemens Energy, n.d.).
8.b. Performance Indicators	
STRENGTHS	Siemens Energy applies internal measures to monitor and understand the impact on the perceptions of society regarding sustainability. Siemens Energy sets specific energy efficiency targets for its turbines and power generation equipment, regularly monitoring and optimising performance to achieve these goals. They track metrics such as heat rate improvements and fuel consumption reductions to drive efficiency gains. Siemens Energy employs leading safety metrics such as Total Recordable Incident Rate (TRIR) and Lost Time Incident Rate (LTIR) to measure and improve safety performance across its operations. They conduct regular safety audits and provide ongoing safety training to employees. Siemens Energy uses metrics such as NPS (Net Promoter Score) and customer retention rates to measure and improve customer satisfaction, promptly addressing any issues or concerns raised. Siemens Energy utilises operational efficiency metrics such as equipment uptime, maintenance costs, and production throughput to optimise plant performance and maximise productivity. They leverage data analytics and predictive maintenance technologies to proactively identify and address inefficiencies. Siemens Energy tracks financial performance indicators such as revenue growth, profit margins, and return on investment (ROI) to assess business performance and financial health (Siemens Energy, 2023).
AREAS FOR IMPROVEMENT (AFI)	While Siemens Energy reports on its sustainability performance, there may be calls for greater transparency and detail in how these reports are compiled and what metrics are included (Siemens Energy, n.d.). Despite improvements, there might be expectations for Siemens Energy to further increase diversity in leadership positions and throughout the company to better reflect societal diversity (Siemens Energy, n.d.). Although Siemens Energy received a low ESG risk rating, indicating a low risk of experiencing material financial impacts from ESG factors, stakeholders might expect more aggressive targets and quicker implementation of ESG initiatives (Siemens Energy, n.d.).

The next company analysed is General Electric Power (Table 3):

Table 3. Criteria for EFQM Excellence Model regarding General Electric Power

1.a. Leaders develop the Mission, Vision, Values and ethics and act as role models.	
STRENGTHS	Leaders of General Electric Power establish and communicate a clear direction and strategic focus on sustainability, emphasising integrity, continuous improvement of their people, communities and the planet. Leaders develop ethics and responsibilities in order to create a culture of integrity. Leaders act as active role models in sustainability programs due to their implication for developing and bringing back into use the derelict properties of the community (General Electric Power, 2022).
AREAS FOR IMPROVEMENT (AFI)	General Electric's mission statement has been criticised for lacking information about organisational activities and how the company plans to achieve the industry leadership goal of the corporate vision statement (Panmore Institute, 2023). The mission and vision statements are meant to keep GE at the forefront of industrial progress, but rapid changes in market dynamics and technology may outpace the company's strategic adjustments (Panmore Institute, 2023).
1.b. Leaders define, monitor, review and drive the improvement of the organisation's management system and performance.	
STRENGTHS	Leaders of General Electric Power emphasise the development for the next suite of engine technologies that provide at least a 20% increase in fuel efficiency compared to current performance. Leaders of General Electric Power develop and improve the organisation's management through developing platforms and smart applications essential for advancing electrification and decarbonisation across the entire energy system (General Electric Power, 2022).
AREAS FOR IMPROVEMENT (AFI)	There have been challenges in ensuring that employees collaborate effectively and make quick business decisions. GE's real-time performance development system aimed to address this issue, but they faced difficulties in breaking down silos within the organisation (Baldassarre and Finken, 2015). The company's ambitious digital transformation has been slow due to distinct coding systems across global businesses, affecting the functioning of apps and overall management efficiency (Untitled Leader, n.d.).
1.c. Leaders engage with external stakeholders.	
STRENGTHS	Leaders promote sustainability programs like returning unused properties, which helps an economic growth and a community development. Leaders of General Electric Power identify strategic and operational partnerships based on organisational and strategic needs, complementary strengths and capabilities. The reason is that GE is a member of the GridWise Alliance, an organisation representing a wide range of stakeholders involved in designing, building, and operating the electric grid in the USA. The alliance also educates key industry participants about the urgent need to modernise the national electricity system (General Electric Power, 2022).
AREAS FOR IMPROVEMENT	The company has been criticised for not communicating effectively with stakeholders, particularly during times of crisis and significant financial losses (Knowledge at Wharton, 2018).

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(AFI)	The reduction of dividends, which once symbolised GE's stability, has been a source of discontent among shareholders (Egan, 2017).
1.e. Leaders ensure that the organisation is flexible and manages change effectively.	
STRENGTHS	Leaders have ensured throughout the 130 years of company history that they adapt and face all the challenges and changes of the organisational environment through the programs that support the company's sustainable goals (e.g. Driving Sustainability Through Transformative Technologies, Lowering Emission with Additive Manufacturing). Leaders ensure that the organisation remains flexible and manages change effectively due to their kaizen spirit of continuous improvement, regularly reviewing their measures and processes to adapt to changes in the external and internal environment (General Electric Power, 2022).
AREAS FOR IMPROVEMENT (AFI)	GE's leadership changes, including the ousting of CEO John Flannery after just 14 months, have been a source of instability and have disrupted the company's change management efforts (Knowledge at Wharton, 2018). GE's ambitious digital transformation encountered significant hurdles, leading to the sale of GE Digital, the organisation at the heart of its transformation. This reflects difficulties in adapting to fast-changing business environments (Knowledge at Wharton, 2018).
2.c. Strategy and supporting policies are developed, reviewed and updated.	
STRENGTHS	General Electric Power's strategy is crafted, implemented, and regularly evaluated to align with the organisation's Mission and Vision, emphasising sustainability. General Electric Power's strategy is reinforced by a strong commitment to decarbonisation and the transition to green energy. General Electric Power integrates the needs and expectations of stakeholders in both the short and long term to meet sustainability goals. General Electric Power identifies its key success factors through its annual sustainability reports. General Electric Power adopts effective methods for anticipating future scenarios such as the resulting climate outcomes and a detailed annual forecast for their CO_2 emission footprint of products and management strategic risks (Siemens Energy, 2023).
AREAS FOR IMPROVEMENT (AFI)	GE poured billions of dollars into its digital strategy, which ultimately did not succeed as planned, leading to the company splitting into three separate entities: GE Aviation, GE Power, and GE Healthcare (Mixson, 2022). More than $100 billion in market value has vanished from GE since November 2016, reflecting the consequences of strategic missteps (Egan, 2017).
3.d. People communicate effectively throughout the organisation.	
STRENGTHS	General Electric Power enables and encourages the sharing information, knowledge and best practices due to their collaboration with universities like Boston University and MIT (General Electric Power, 2022). General Electric Power provides clear guidance and strategic focus for their team through the GE Human Rights Statement of Principles (General Electric Power, 2022).
AREAS FOR IMPROVEMENT (AFI)	During the digital transformation, there were communication breakdowns within the company. Engineers found that integrating data from various global businesses into a single platform was slow due to distinct coding systems, which affected the functioning of apps and overall management efficiency (Mixson, 2022). There was a reported data breach against GE, where threat actors accessed confidential information. This incident points to potential communication issues regarding cybersecurity and the protection of sensitive data (RestorePrivacy, 2023).
3.e. People are rewarded, recognised and cared for.	
STRENGTHS	One of General Electric Power's top Priorities is the effort to make the health and well-being of their employees. In recognition of their work, the company received the 2022 Best Employers: Excellence in Health and Well-Being Award from the Business Group on Health (General Electric Power, 2022). At General Electric Power, people are rewarded, recognised and cared for through respecting workers' rights to freedom of association, privacy, collective bargaining, immigration, working time, wages and hours, and prohibits forced, compulsory and child labour and employment discrimination in new business operations and partnerships (General Electric Power, 2022).
AREAS FOR IMPROVEMENT (AFI)	GE was once respected for its management prowess, but over the last two decades, the company has faced a slow-motion implosion, which likely affected employee morale and the perceived value of rewards (Axios, 2021).
4.c. Buildings, equipment, materials and natural resources are managed in a sustainable way	
STRENGTHS	General Electric Power bases its resource utilisation on the principles of circular economy to ensure that their management is sustainable (General Electric Power, 2022). General Electric Power uses their resources in a way to protect the environment, namely they use lost materials, redirecting them back to the economy instead of using virgin materials (General Electric Power, 2022).
AREAS FOR IMPROVEMENT (AFI)	Supply chain disruptions and shortages continue to impact GE's renewable energy business, affecting the company's ability to manage resources effectively (Mixson, 2022).
5.d. Products and Services are produced, delivered and managed.	
STRENGTHS	General Electric Power oversee products and services throughout their entire lifecycle driven by their commitment to a more circular economy, including the lifecycle of their engines. Currently, their catalogue includes over 23,000 total repairs to restore worn GE and CFM International engine parts to serviceable condition. Additionally, GE and CFM International industrialised more than 1,700 repairs in 2022, enhancing repair capabilities. Consequently, GE repaired approximately 2.3 million engine components globally in 2022 (General Electric Power, 2022).

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	General Electric Power creates and provides products and services that meet or surpass customer expectations through currently having 100% H_2-capability across some of its gas turbine offerings. It is expanding its capability with industry-leading, efficient gas turbines to 100% by 2030 to meet customer needs to future-proof investments as hydrogen becomes available (General Electric Power, 2022).
AREAS FOR IMPROVEMENT (AFI)	The company's financial struggles, including a nightmare cash crunch, could impact its ability to manage products effectively and maintain competitive compensation practices (Egan, 2017).
8.a. Perception	
STRENGTHS	General Electric Power performs regular surveys to obtain the societies' perception of the organisation, such as employee surveys, customer surveys, supplier surveys, selected members survey, investor surveys, community surveys, 2022 Best Employers: Excellence in Health & Well-being Award (General Electric Power, 2022). General Electric Power initiates measures following the questionnaires for the areas of environmental impact and for social impact (General Electric Power, 2022).
AREAS FOR IMPROVEMENT (AFI)	GE has experienced one of the greatest downfalls in business history, with a significant reduction in workforce and a precipitous fall in share price. This downfall has impacted the public's perception of GE as a stable and reliable company (Gates, 2021). GE's leadership, including former CEOs Jack Welch and Jeff Immelt, has been criticised for questionable deal-making and strategic decisions that have led to the company's current challenges (Egan, 2017).
8.b. Performance Indicators	
STRENGTHS	General Electric Power applies Performance Indicators on Sustainability in order to predict and improve the performance of the organisation (e.g. of categories human rights: Supplier Responsibility Program, Environmental Stewardship, Diversity and Inclusion, Safety, Lifting Our Communities) (General Electric Power, 2022). General Electric internal indicators provide a clear assessment of the effectiveness of various adoptive approaches such as sustainable progress across its supply chain and individual sustainable performance (General Electric Power, 2022).
AREAS FOR IMPROVEMENT (AFI)	Based on a scoring method by GuruFocus, GE was assigned a score that signals poor future outperformance potential (Yahoo Finance, 2023).

The last company analysed according to the EFQM Excellence Model is Mitsubishi Power (Table 4).

Table 4. Criteria for EFQM Excellence Model regarding Mitsubishi Power

1.a. Leaders develop the Mission, Vision, Values and ethics and act as role models.	
STRENGTHS	Leaders of Mitsubishi Power develop and set a clear mission for the company in order to contribute to sustainable society through their business activities, likely: Care for the planet, Create a more harmonious society and Inspire the future. Leaders of Mitsubishi Power communicate the mission, vision and values to the employees and stakeholders through various channels such as the company website, rapports (Sustainable Rapports), meetings, workshops, visible papers etc. (Mitsubishi Power, 2023).
AREAS FOR IMPROVEMENT (AFI)	Leaders should ensure that the mission and vision are communicated clearly and consistently across all levels of the organisation (Mitsubishi Power Americas, n.d.). Mitsubishi Power should invest in leadership development programs to ensure leaders at all levels understand and can effectively communicate the mission and vision (Mitsubishi Power Americas, n.d.). Mitsubishi Power should integrate the mission and vision into the company culture to guide decision-making and behaviour at all levels (Mitsubishi Power Americas, n.d.).
1.b. Leaders establish, oversee, assess, and advance the enhancement of the organisation's management system and performance.	
STRENGTHS	Leaders of Mitsubishi Power define and a improve a Sustainability Promotion System, with a Sustainability Committee which has a general objective promoting a management that considers sustainability in all the activities of the company. Leaders of Mitsubishi Power review their sustainability system through the Materiality Council, where problems regarding the progress, project examples and questions/ opinions are discussed (Mitsubishi Power, 2023).
AREAS FOR IMPROVEMENT (AFI)	Leaders of Mitsubishi Power should, as the world moves towards a more sustainable future, continue to improve its management system by integrating more renewable energy sources into its portfolio (Power Engineering, 2020). Leaders of Mitsubishi Power should strengthen global partnerships and collaborations, which may lead to shared innovation and improved management practices. This can also include integrating systems from other companies to create a more cohesive energy management system (Mitsubishi Power, n.d.).
1.c. Leaders engage with external stakeholders.	
STRENGTHS	Leaders of Mitsubishi Power maintain a transparent and clear communication with their stakeholders and transfer to them their sustainability priorities and principles, expectations and business activities following a CSR Action Guide. Leaders of Mitsubishi Power engage with their stakeholders through a Basic Policy on Environmental Matters and Action Guidelines to promote environmental initiatives and dialogues with their stakeholders (Mitsubishi Power, 2023).

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AREAS FOR IMPROVEMENT (AFI)	□ Leaders should involve stakeholders in the development and refinement of the mission and vision to ensure they are relevant and impactful (Mitsubishi Power Americas, n.d.). □ Strengthening global partnerships and collaborations can lead to shared innovation and improved management practices. This can also include integrating systems from other companies to create a more cohesive energy management system (Mitsubishi Power Americas, n.d.).
1.e. Leaders ensure that the organisation is flexible and manages change effectively.	
STRENGTHS	□ Leaders of Mitsubishi Power stay informed and continuously adapt to societal changes, integrating sustainable AI and digital products to meet company needs. They leverage digitalisation to manage customer demands sustainably and encourage creativity among their employee. □ Leaders of Mitsubishi Power build a flexible, robust and labour-saving system (MBA Skool, 2023), which helps them to contribute to a sustainable society (Mitsubishi Power, 2023).
AREAS FOR IMPROVEMENT (AFI)	□ Leaders of Mitsubishi Power should implement in advanced digital solutions like artificial intelligence and machine learning, which may optimise power plant performance and reduce carbon emissions. Mitsubishi Power's TOMONI suite of intelligent digital solutions is a step in this direction (BusinessWorld Online, 2021).
2.c. Strategy and supporting policies are developed, reviewed and updated.	
STRENGTHS	□ Strategies and supporting policies are continuously developed and updated by the Chief Strategy Officer and Chief Sustainable Officer with the Sustainable Committee, in order to sustain and empower a growth of the company with fairness, integrity and responsibility to society (Mitsubishi Power, 2023). □ Strategies and supporting policies are reviewed continuously based on the outcomes of the company's effectiveness evaluation (MBA Skool, 2023) and are approved by the Board of Directors (Mitsubishi Power, 2023).
AREAS FOR IMPROVEMENT (AFI)	□ Mitsubishi Power can enhance its strategy by staying agile and responsive to the rapid changes in the global energy market, such as shifts in fuel prices, regulatory changes, and the evolving competitive landscape (Mitsubishi Electric, 2023).
3.d. People communicate effectively throughout the organisation.	
STRENGTHS	□ People in Mitsubishi Power communicate effectively in the organisation through a well-established management of the organisation. There is a Chief Sustainable Officer who is responsible for the sustainable direction of the company, namely, to make executive decisions on how to tackle sustainability issues, such as ESG initiatives (Mitsubishi Power, 2023). □ Mitsubishi Power facilitates and promotes the sharing of information and best practices across the organisation dialogues thanks to the MHI Power Human Rights Policy that includes the adherence to laws and regulations regarding human rights, includes targets, education and responsibilities related to respecting human rights, human rights due diligence, dialogue and consultation, and information disclosure (Mitsubishi Power, 2023).
AREAS FOR IMPROVEMENT (AFI)	□ Mitsubishi Power should develop a diverse and versatile talent pool through strategic human resource initiatives, which may foster innovation and business growth (BusinessWorld Online, 2021). □ Mitsubishi Power should implement training programs focused on communication skills, which may help employees convey their ideas more effectively and enhance teamwork (Mitsubishi Power, n.d.)
3.e. People are rewarded, recognised and cared for.	
STRENGTHS	□ Both internal and external members of Mitsubishi Power are encouraged to engage in activities that benefit the broader community such as: Science classes, Factory tours with hands-on learning, Career education, Sports coaching, Study support and Sponsoring of Scholarships. □ Mitsubishi Power ensures an embracement of diversity for the people through the MHI Power Human Rights Policy and through their principle of act with integrity and fairness, always respecting others (Mitsubishi Power, 2023).
AREAS FOR IMPROVEMENT (AFI)	□ Mitsubishi Power should offer career development opportunities, such as tuition reimbursement or training programs, which may help employees grow professionally and feel more invested in the company (Mitsubishi Electric Americas, n.d.). □ Mitsubishi Power should develop recognition programs that celebrate employee achievements, such as 'Employee of the Month' or 'Going the Extra Mile' awards, which may boost morale and encourage a culture of excellence (Mitsubishi Electric Americas, n.d.)
4.c. Buildings, equipment, materials and natural resources are managed in a sustainable way	
STRENGTHS	□ Mitsubishi Power optimises resource and asset use throughout their lifecycle to minimise environmental impact across all company operations, including product R&D and design, raw material procurement, manufacturing, transportation, usage, servicing, and disposal, through pollution prevention, resource conservation, energy efficiency, and waste reduction (Mitsubishi Power, 2023). □ Mitsubishi Power applies suitable policies and strategies to preserve the environment and contribute to solving environmental and energy challenges (Mitsubishi Power, 2023).
AREAS FOR IMPROVEMENT (AFI)	□ Mitsubishi Power should implement advanced digital solutions like artificial intelligence and machine learning, which may optimise power plant performance and reduce carbon emissions. Mitsubishi Power's TOMONI suite of intelligent digital solutions is a step in this direction (BusinessWorld Online, 2021).

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5.d. Products and Services are produced, delivered and managed.	
STRENGTHS	Mitsubishi Power optimises resource and asset use throughout their lifecycle to minimise environmental impact throughout all company activities, from product R&D and design to raw material procurement, manufacturing, transportation, usage, servicing, and disposal, by focusing on pollution prevention, resource conservation, energy efficiency, and waste reduction (Mitsubishi Power, 2023). Mitsubishi Power enforces relevant policies and strategies to preserve the environment and contribute to solving environmental and energy challenges (Mitsubishi Power, 2023).
AREAS FOR IMPROVEMENT (AFI)	Mitsubishi Power should improve customer service by providing innovative technologies to reduce pollutants, manage multi-fuel applications, and supply and manage SCR (selective catalytic reduction) catalysts, which may enhance overall service quality (Mitsubishi Power, n.d.).

8.a. Perception	
STRENGTHS	Mitsubishi Power conducts internal and external surveys to understand the society's perception of their company analysing the human resources aspects, environment impact aspect, quality of the projects etc. (Mitsubishi Power, 2023). Mitsubishi Power has a strong commitment to society and uses transparent communication with stakeholders due their awards in Recognising Outstanding Environmental Contributions through MHI's Best Innovation Awards, and obtained Incentives Toward Management Activities Related to the Issue of Climate Change (Mitsubishi Power, 2023).
AREAS FOR IMPROVEMENT (AFI)	Mitsubishi Power should enhance the customer experience by providing tailored solutions and services, which may strengthen relationships and drive business success (Mitsubishi Electric, 2023).
8.b. Performance Indicators	
STRENGTHS	Mitsubishi Power uses internal measures and indicators to track, analyse, and enhance the company's performance regarding societal and environmental responsibilities, such as reduce co_2 emissions, number of optimal energy infrastructures, level of employees' awareness, increase the ratio of women on the Board of Directors, reduce the number of accidents etc. (Mitsubishi Power, 2023). Mitsubishi Power's indicators provide an understanding of the approaches adopted and their impact on society and environment such as reduction in CO_2 emissions, reduction in water usage, reduction in waste generation (Mitsubishi Power, 2023).
AREAS FOR IMPROVEMENT (AFI)	Mitsubishi Power established performance metrics that are tied to the company's mission and vision to measure progress and drive accountability (Mitsubishi Power Americas, n.d.).

As can be seen, all three companies demonstrate strong sustainability practices, positioning them as market leaders in sustainable organisational performance. However, they also encounter some less favourable activities in this domain, which present opportunities for improvement. By addressing these areas, they can further enhance their achievement of sustainability objectives. The next section will present the results of this analysis.

3. Results and discussion

The results of this paper are based on the preceding analysis of the companies and the identification of practices to adopt or avoid to achieve organisational excellence in sustainability and their impact on the community. Siemens Energy is dedicated to the energy transition and has established ambitious decarbonisation targets across its entire value chain. The company aims to achieve 100% renewable electricity in its operations by 2023 and is on track to meet its decarbonisation goals. Siemens Energy prioritises offering decarbonised products, services, and solutions to its customers, with a goal to reduce absolute Scope 3 greenhouse gas emissions from the use of sold products by 28% by 2030.

Similarly, General Electric adopts a comprehensive approach to sustainability, focusing on decarbonisation through the energy transition, developing smarter aviation solutions, and enabling precision healthcare. The company is committed to achieving carbon neutrality by 2030 and aims for net zero Scope 3 emissions from using sold products by 2050. GE's sustainability strategy includes a strong culture of integrity, product safety and quality, diversity and inclusion. Additionally, GE is preparing to separate its energy businesses into GE Vernova, which will concentrate on electrifying and decarbonising the world.

Lastly, Mitsubishi Power aims to address social issues through its reliable manufacturing technology and seeks to grow alongside the global community. Their sustainability efforts focus on environmentally conscious design, resource recycling initiatives, and developing products and technologies that tackle environmental challenges. Mitsubishi Power has identified five key areas of material importance to solve social challenges through their business operations and strengthen their foundation for sustainable growth.

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A synthetic summary of this comparative analysis could be organised in a table format (see Table 5), in which the main good practices collected from these three companies are highlighted, together with the possibilities of transferring these to another different types of companies or across different industries.

Table 5. Benchmarking Summary

Criterion	**Good practices of these analysed companies**	**Can be transferred/ used to SMEs (small and medium sized enterprises) as well**	**Can be transferred/ used to other industries**
1.a. Leaders develop the Mission, Vision, Values and ethics and act as role models.	Leaders develop and define the companies' main sustainability goals and integrate them in their industrial processes or business activities. Leaders disseminate the sustainability strategy in the company through rapports, meetings, workshops, internal papers etc. and act as role models engaging themselves in projects for achieving these objectives.	✓	✓
1.b. Leaders establish, oversee, assess, and advance the enhancement of the organisation's management system and performance.	Leaders review and drive permanently the improvement of the Integrated Management System of their companies through developing platforms and smart applications for advancing the Management of Documents. They also create adjacent systems such as Sustainability Promotion System and Company Councils to analysed and improved all these systems.	**X** Resources needed	✓
1.c. Leaders engage with external stakeholders.	Leaders engage in market analysis with different stakeholders in order to take part in activities that foster the environmental impact of the companies in the energy sector and create alliances to design, build, operate etc. different electric grids and modernise the energy sector worldwide.	✓	**X** Sector related
1.e. Leaders ensure that the organisation is flexible and manages change effectively.	Leaders ensure that the company remain flexible through different methods like using Kaizen methodology and continuously measuring and reviewing their processes, training their employees and even through using Artificial Intelligence products.	**X** Resources needed	✓
2.c. Strategy and supporting policies are developed, reviewed and updated.	Companies' strategy is developed by specific Sustainable Committees, focusing on the need and expectations of stakeholders in sustainability and present them in reports.	**X** Resources needed	✓
3.d. People communicate effectively throughout the organisation.	Communication in the company is realised through specific channels or systems to facilitate and foster the engagement and create robust procedure framework and guidance.	✓	✓
3.e. People are rewarded, recognised and cared for.	People are cared for through the effort of improving their health and well-being, respecting their rights to freedom, investing in their self-development, sharing knowledge, creating a culture of rewarding and promotion and also a culture of inclusion and diversity.	✓	✓
4.c. Buildings, equipment, materials and natural resources are managed in a sustainable way	The old equipment is changed to new one for improving the energy saving process, natural resources are use for producing green energy, all the equipment and processes are transformed for producing less gas emissions and introducing the concept of circular economy. They also manage the entire lifecycle of a product in a sustainability perspective. Policies and strategies to preserve the environment are also created.	**X** Resources needed	✓
5.d. Products and Services are produced, delivered and managed.	Products are designed and produce in a sustainable way and the maintenance process is also reformulated for a greener economy.	**X** Resources needed	✓
8.a. Perception	A lot of operational surveys are conducted through the company's stakeholders to improve the sustainability approach and stakeholder engagement strategies based on feedback, lessons learned, and emerging trends. Gaining different awards as a recognition of merits in the sustainability field.	**X** Resources needed	✓
8.b. Performance Indicators	Total Recordable Incident Rate (TRIR) and Lost Time Incident Rate (LTIR) are indicators used to measure and improve safety performance across operations. Using also financial indicators, Net Promotion Score, Reduce CO_2 emissions, Number of optimal energy infrastructures, Level of employees' awareness, Increase the ratio of women on the Board of Directors, Performance Indicators in Sustainability (Supplier Responsibility Program, Environmental Stewardship, Diversity and Inclusion, Safety, Lifting Our Communities) helped the companies to understand their position on market regarding sustainability.	**X** Resources needed	✓

Next, based on the analysis and the statements above, we can extract and synthesise both the best practices and those to avoid in the field of sustainability for each company. These practices are influenced by the specific regions where each company is headquartered. The findings are presented below for Siemens Energy first:

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- Investing in Renewable Energy, namely using renewable energy sources for their operations;
- Using or improving a sustainable supply-chain, namely ensuring that suppliers adhere to environmental and social standards;
- Creating energy-efficient products, namely designing and developing products that use less energy and resources that affect the environment.

Further, from General Electric the following good practices must be highlighted:

- Improving and foster employee engagement and sustaining integrity in their organisation;
- Focusing in Innovation and Research & Development, namely they are investing significantly for global innovation to develop sustainable technologies;
- They enhance Product Quality and Safety programs to uphold highest standards;
- Progressing toward a 2030 Carbon Neutrality Commitment and a Net Zero target from the use of sold products by 2050.

From Mitsubishi Power some other good practices may be learnt:

- They aim to create a clean power generation with 100% hydrogen and natural gas-fired cogeneration facilities and also they proceed to fast-forwarding decarbonisation in Taiwan with this and natural gas-fired cogeneration facilities and to develop a new model for sustainable power generation in Jakarta by transitioning from coal to natural gas;
- They focus on implementing processes to minimise waste production and promote recycling and reuse;
- Protect and restore natural habitats and ecosystems, continuously seeking new ways to improve sustainability performance.

Additionally, areas for improvement in sustainability, specifically practices to avoid, have been identified for each company. For Siemens Energy, the practices to be avoided are as follows.

- Siemens Energy underestimated the complexity and challenges of scaling up their wind turbine operations, resulting in a gap between their strategic ambitions and operational capabilities.
- Leaders did not adequately anticipate or identify stakeholder perceptions that could lead to conflicts, essential for ensuring smooth operations and maintaining a good reputation in customer projects.
- Leaders have communicated inadequately with stakeholders, including shareholders and government entities, and may not have been sufficiently proactive or transparent during times of crisis.
- Siemens Energy is challenged by high energy costs, which, along with investing in sustainability and energy efficiency, also affects its competitiveness.

The following points refer to the General Electric company:

- General Electric's mission statement lacks information about organisational activities and how the company plans to achieve the industry leadership goal of the corporate vision statement.
- General Electric's ambitious digital transformation faced significant hurdles, ultimately leading to the sale of GE Digital, the core of its transformation efforts, highlighting the challenges of adapting to rapidly changing business environments.
- During the digital transformation, General Electric experienced communication breakdowns, which negatively impacted app functionality and overall management efficiency.

The last company whose practices to avoid were analysed is Mitsubishi as follows:

- Mitsubishi Power should prioritise investment in leadership development programs to ensure that leaders at every level comprehend and can proficiently communicate the company's mission and vision.
- Leaders of Mitsubishi Power do not invest in advanced digital solutions like artificial intelligence and machine learning. Digital tools can make companies work better and care more for the environment. Using new tech in the EFQM Model helps companies do well by being quick to change and focus on green goals and can optimise power plant performance and reduce carbon emissions (Vokony, Taczi, & Szalmane Csete, 2020).
- Mitsubishi Power does not have a diverse and versatile talent pool through strategic human resource initiatives that can foster innovation and business growth.
- Mitsubishi Power slowly improves customer experience by offering customised solutions and services, which can bolster relationships and contribute to business success.

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4. Conclusion

This paper's goal was to present a comparative analysis of three companies in the energy sector from different regions of the world, focusing on their sustainable practices. This analysis, based on the method of the EFQM Excellence model, aims to provide directions for further improvements and highlight practices to avoid in the realm of sustainability. Siemens Energy, General Electric Power and Mitsubishi Power are industry leaders striving for a more sustainable future, reflecting corporate responsibility and responding to the global demand for environmental stewardship. These aspects represent very interesting approaches to being studied in future works.

Siemens Energy stands out with its commitment to renewable energy and diversity. They set a benchmark with ambitious decarbonisation targets and an inclusive workplace culture. Their proactive approach to achieving 100% renewable electricity and reducing greenhouse gas emissions sets a clear example for others in the industry. General Electric Power (GE), known for its innovation, continues to advance sustainability. GE's dedication to carbon neutrality and developing sustainable technologies shows its understanding that long-term success is tied to the planet's health. Their investment in R&D and product safety makes sustainability a tangible goal. Mitsubishi Power focuses on clean power generation and regional decarbonisation. Their transition from coal to natural gas in Jakarta and promotion of clean power with hydrogen technology highlight the urgent need for change in energy production and consumption.

While these companies exemplify good practices, the sustainability journey is challenging. Avoiding unsustainable practices, such as inadequate emissions controls, poor waste management, and lack of transparency, is as crucial as implementing positive actions. These challenges will test the resolve and innovation of these industry leaders. Looking ahead, the collective actions of Siemens Energy, General Electric Power, and Mitsubishi Power will shape their legacies and our global society. Their ongoing commitment to sustainability will serve as a beacon for others, guiding us towards a more resilient and equitable world. The balance of good and to-avoid practices will determine their success, and the world watches with hopeful anticipation for their next steps on this green journey.

In conclusion, this work presented a comparative analysis of three market-leading companies in the energy sector on the issue of sustainability in achieving organisational performance, having as a guiding framework the criteria of the EFQM Excellence Model, practices with potential transfer to other industries and with complementary resources, to SMEs.

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References

Aaron Hall (2024) Driving Change at Siemens: From Scandal to Global Transformation URL: https://aaronhall.com/driving-change-at-siemens-from-scandal-to-global-transformation/ (Accessed on April 2024*)*

Axios (2024): What went wrong at General Electric URL: https://www.axios.com/2021/11/09/what-went-wrong-general-electric (Accessed on April 2024*)*

Balcioğlu, Y. S., Çelik, A. A., Altindağ, E. (2024). Artificial Intelligence Integration in Sustainable Business Practices: A Text Mining Analysis of USA Firms. *Sustainability*. 16(15), 6334. DOI: https://doi.org/nj9d

Baldassarre, L., Finken B. (2015). GE's Real-Time Performance Development. *Harvard Business Review*. URL: GE's Real-Time Performance Development (hbr.org) (Accessed on April 2024)

Business World (2021) Mitsubishi Power plans to roll out 'smart' power plants URL: https://www.bworldonline.com/corporate/2021/07/02/379692/mitsubishi-power-plans-to-roll-out-smart-power-plants/ (Accessed on April 2024*)*

Chungyalpa, W. (2021). Understanding Business Sustainability: The What, the Why, and the How of Sustainable Business Practices. *Indian Journal of Sustainable Development*. 5(1–2), 24–37. URL: https://www.researchgate.net/publication/352837459_Understanding_Business_Sustainability_The_What_the_Why_and_the_How_of_Sustainable_Business_Practices

Conțu, E. G. (2020). Organisational performance – theoretical and practical approaches; study on students' perceptions. *Proceedings of the International Conference on Business Excellence*. 14(1), 398–406. DOI: https://doi.org/nj9f

Egan Matt (2017) How decades of bad decisions broke GE, URL: https://money.cnn.com/2017/11/20/investing/general-electric-immelt-what-went-wrong/index.html (Accessed on April 2024)

Eskildsen, J. K., Dahlgaard, J. J. (2000). A causal model for employee satisfaction. *Total Quality Management.*11(8), 1081–1094. DOI: https://doi.org/ft7k62

European Comission (1987). Report of World Commission on Environment and Development: Our Common Future; *Oxford University Press: Oxford, UK,*

Fauzi, H., Svensson, G., Rahman, A. A. (2010). "Triple Bottom Line" as "Sustainable Corporate Performance": A Proposition for the Future. *Sustainability*. 2(5), 1345–1360. DOI: https://doi.org/dn3nqp

General Electric (2024): The energy to change the world URL: https://www.gevernova.com/ (Accessed on July 2024).

General Electric, (2022) Sustainable Report. *General Electric Power*. URL: https://www.ge.com/sites/default/files/ge2022_sustainability_executive_summary_en.pdf

https://doi.org/10.55343/CogSust.117

Gurufocus (2023), General Electric Co (GE): A Deep Dive into Its Performance Potential URL: https://finance.yahoo.com/news/general-electric-co-ge-deep-160632403.html?guccounter=1&guce_referrer=aHR0cHM6Ly93d3cuYmluZy5jb20v&guce_referrer_sig=AQAAAHn-H98aQQN7_jsD0CiqtuD-hV8HkCagiLVVLDfYMr2Qv4rO0bWEQwLYUj9JoyOWslHeQsJTuMs5nGokiBt2lqZ0_N89M9LaiyBRpF6njK_Xh3t1I0G9_Ly9cEGU_bXPvnSJiur1__-7HAjSRwFlIrNwAeUvag2K9fOzYo_ZvGvg (Accessed on April 2024)

Heinrich Long (2023), Hackers Claim Attack on General Electric, Leak Data Samples. URL: https://restoreprivacy.com/hackers-claim-attack-on-general-electric-leak-data-samples/ (Accessed on April 2024)

Jennifer Runyon (2020) Mitsubishi Hitachi Power Systems rebrands, drops Hitachi and systems. URL: https://www.power-eng.com/news/mitsubishi-hitachi-power-systems-rebrands-drops-hitachi-and-systems/ (Accessed on April 2024)

Knowledge at Warton (2018) GE's Leadership Problem Goes Beyond Its CEO. URL: https://knowledge.wharton.upenn.edu/podcast/knowledge-at-wharton-podcast/what-does-the-future-hold-for-ge/ (Accessed on April 2024)

Looy, A. V., Shafagatova, A. (2016). Business process performance measurement: a structured literature review of indicators, measures and metrics. *SpringerPlus*. 5(1), 1797. DOI: https://doi.org/ghh78p

Mitsubishi Power (2023) Integrated Report URL: https://www.mitsubishielectric.com/en/investors/library/integrated_report/pdf/2023/6.pdf

Mitsubishi Power (2024), Mitsubishi Services URL: https://power.mhi.com/service (Accessed on April 2024)

Mitsubishi Power, (2023) Mitsubishi Power, Sustainability Report. URL: https://www.mitsubishi-motors.com/en/sustainability/pdf/report-2023/sustainability2023.pdf?20231110

Mitsubishi Power, (2024) Digital solutions URL: https://www.changeinpower.com/digitalization/ (Accessed on April 2024)

Mitsubishi Power, (2024). Mitsubishi Heavy Industries, Ltd. URL: https://power.mhi.com/company/outline/profile.pdf (Accessed on July 2024)

Mixson, E. (2022). Lessons learned from GE's Digital Transformation Failure. *Intelligent Automation Network*. URL: Lessons learned from GE's Digital Transformation Failure (intelligentautomation.network)

Olaru, M., Stoleriu, G., Şandru, I. M. D. (2011). Social Responsibility Concerns of SMEs in Romania, from the Perspective of the Requirements of the EFQM European Excellence Model. *Amfiteatru Economic*. 13(29), 56–71.

Panmore Institute (2023) General Electric (GE) Mission Statement & Vision Statement (An Analysis) URL: https://panmore.com/general-electric-ge-vision-statement-mission-statement (Accessed on April 2024)

Powering Success: Powering Success: Leadership Lessons and Stories from General Electric. (n. d.) *Untitled Leader*. Powering Success: Leadership Lessons and Stories from General Electric (untitledleader.com)

Santos-Vijande, M. L., Alvarez-Gonzalez, L. I. (2007). TQM and firms performance: An EFQM excellence model research based survey. *International Journal of Business Science and Applied Management*. 2(2), 21–41.

Severin, I. (2023/2024). Integrated Management Systems. *Course Support*. National University of Science and Technology POLITEHNICA Bucharest.

Severin, I., Dijmarescu, M. C., Caramihai, M. (2022). Sustainability and excellence: Pillars for business survival. In: Mori, M. (ed.), *Globalization and Sustainability – Recent Advances, New Perspectives and Emerging Issues*. IntechOpen. DOI: https://doi.org/nj9h

Siemens Energy (2024) Siemens Energy AG - Company Profile URL: https://www.globaldata.com/company-profile/siemens-energy-ag/swot-analysis/ (Accessed on April 2024)

Siemens Energy (2024) Siemens Energy Press Site. URL: https://press.siemens.com/global/en (Accessed on April 2024)

Siemens Energy, (2023) Siemens Energy Sustainable Report. URL: https://p3.aprimocdn.net/siemensenergy/d66ceb42-cf25-45d4-9cd1-b0cf00ce4ca9/Siemens-Energy_Sustainability-Report-2023-pdf_Original%20file.pdf

Siemens Energy, (2024). Company presentation Siemens AG. URL: https://www.globaldata.com/company-profile/siemens-energy-ag/ (Accessed on July 2024)

Vokony, I., Taczi, I., Szalmane Csete, M. (2020). Agile digitalisation evolution in the energy sector, taking into account innovative and disruptive technologies. *Renewable Energy and Power Quality Journal*. 20, 584–589. DOI: https://doi.org/nj9j

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Analysis and Control of the Gearshift Process Based on a Dog Clutch Shiftability Mode

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Abstract

This paper deals with gearshift control using a face dog clutch as a shifting element. Based on our previous work on dog clutch kinematics, the paper identifies optimal control parameters, such as the angular position difference at which the gearshift process can start and the linear reference position trajectory. The robustness of the control parameters is shown. Further on, a gearshift mechanism dynamic model is developed, describing elements of an existing gearbox with shifting elements guided by a rotating disc. The coupled linear and torsional dynamics of the actuated shifting mechanism are analyzed. Finally, a linear quadratic regulator is designed and tested in a model in the loop environment for the requested reference trajectory to show the feasibility of the presented method. Three gearshift cases are considered, and the results show that the developed controller can perform a successful gearshift without experiencing a face impact between the gear and the sliding sleeve teeth in order to enhance sustainability.

Keywords

Dog Clutch, Control Design, Gearshift, Shiftability, Shifting Mechanism, Simulation

1 . Introduction

1.1 . Necessity and classification of gearboxes

Nonrenewable fuel shortages and environmental problems are becoming increasingly pressing global issues, leading the world towards renewable energy sources (Al-Oran et al., 2020) and clean, efficient systems (Burgelman and Grove, 2010). As a result, motor vehicles, including all their subsystems, are receiving more attention for their performance (Alzyod and Ficzere, 2021; Alsardia et al., 2021; Nguyen et al., 2021), efficiency and ability to adopt clean energy concepts (Mallouh et al., 2010, Liu et al., 2021).

Motor vehicles can be cleaner for the environment by optimizing system parameters to be more efficient (Milovančević et al., 2022), specifically the engine and the transmission. Regarding the engine, engine efficiency and alternative fuels can be improved. (Mallouh et al., 2010, Liu et al., 2021, Obeidi et al., 2018)

The development of motor vehicles driven by internal combustion engines (ICE) required the introduction of multi-gear ratio transmissions. The transmission performance depends on several parameters, such as internal structure and operation, power transfer, and gearshift elements.

The operation of a gearbox happens at three levels. The first level is the user interface. At this level, the driver engages in the forward or reverse directions or the neutral position. The driver operates at this level. The second level is the selection of the optimal transmission ratio. The driver can select an algorithm coded in hardware or software. The third level is the mechanical engagement of the selected gear ratio. The driver or an actuated mechanism can also make this level.

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From the driver's point of view, vehicle transmission can be classified into two main categories: manual (MT) and automatic (AT). In the manual case, the driver acts at all three levels. In the automatic case, the driver acts only at the first level. Note that in the case of automatic gearboxes, the physical realization and the gear engagement system can be of any convenient type. During the vehicle's operation, the vehicle's selected transmission ratio is influenced by the actual vehicle driving conditions. It is determined by the vehicle's driver in a conventional manual transmission (MT) or by a transmission control unit (TCU) in an automatic transmission. Compared to MT, a TCU chooses more precisely the appropriate gear ratio to operate the ICE in its most efficient torque or power range for a given vehicle load (Rudolph et al., 2007).

Different structures have been developed to provide automatic transmission, such as conventional AT with planetary gearsets, continuously variable transmission (CVT), automated manual transmission (AMT), and dual-clutch transmission (DCT). According to the Council (2015), AT and CVT are better at driving comfort, while MT and AMT are better at efficiency and cost. Regarding driving pleasure, MT and DCT have the edge (Greiner and Grumbach, 2013). In the future, DCTs, ATs, and CVTs are estimated to dominate the passenger car market, while AMTs and MTs will be exclusive in the commercial vehicle market (Xu et al., 2018).

1.2 . Presentation of the Dog Clutch in the literature

Two traditional solutions exist to fulfil the requirements of easy, silent and smooth gearshift: the synchronizer for manual transmissions and the multi-surface friction clutch for conventional automatic transmissions.. Discussion of the synchronizer and the MSFC supposes that the vehicle's power transmission is partially or completely interrupted at the actual moment, and the research studies phenomena within a short time window (tenths of seconds), before closing the main clutch. Here, we consider the processes at the level of gearbox operation inside the gearbox housing within the duration of the jerk.

The synchronizer has been studied by many researchers (Socin and Walters, 1968; Lovas et al., 2006b; Lovas et al., 2006a). It remained the common gearshift mechanism for many decades, but fuel shortage and environmental issues launched the search for a more efficient system. Initially designed for human operation, the synchronizer employs friction for input-output speed synchronization and stopping mechanisms to empeach gear engagement at high angular velocity difference. Thus, it is not easy to actuate, and it constrains the size of the gearbox.

Dog teeth clutch has been replacing the synchronizer because it provides quicker shifting time, simpler structure, larger power transmitting capacity in identical volume, and has a lower cost (Shiotsu et al., 2019; Vierk and Kowal, 2018), which grants it great potential in several aspects. Heavy-duty electric vehicle (EV) efficiency can be improved by applying multi-speed gearboxes in the transmission chain (Tseng and Yu, 2015). Because of its efficiency, these transmissions employ clutchless automated manual transmission (AMT), using dog clutch as a shifting element. Commercial vehicles equipped with AMT employ the dog clutch as a gearshift element due to its strength and long service life (Bóka et al., 2009).

However, as the mechanical speed synchronization mechanism (the friction mechanism) is missing, the speed synchronization must be a part of the gearshift control. EVs and commercial vehicles utilize an external synchronization strategy for speed synchronization. In the case of EVs employing clutchless AMTs, speed synchronization is achieved by electric motor control (Walker et al., 2017). Commercial vehicles' AMT includes a transmission brake on the gearbox countershaft to set the required low mismatch speed (Bóka et al., 2010a).

In many cases, these strategies cannot be applied. In the case of motorcycles, there is no space to install these components. Also, some conventional ATs utilize the dog clutch as an interlocking element instead of MFSC for fuel efficiency (Dick et al., 2013). In such cases, the gearshift process occurs without speed synchronization, so the shifting process has to be investigated to achieve successful dog clutch engagement.

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To the authors' knowledge, these problems were first studied by Laird (1990), who studied the radial and face dog clutch (discussed later) for heavy-duty commercial vehicles. Bóka et al. (2010b) studied the application of the dog clutch shiftability in AMT for commercial vehicles. He used the notion of engagement probability to find a certain successful region depending on the initial mismatch speed and formulated the necessary equations to guarantee successful engagement at a low mismatch speed (below four rad/s).

Later on, Farkas and Lovas (4p, 2014) investigated the engagement process from a kinematical point of view. They developed a geometric condition for successful engagement under constant axial speed and developed a two-dimensional shiftability map. Their results showed a periodicity in the successful shifting region.

In their thesis, Eriksson et al. (2013) conducted a study on the dog clutch used in truck transfer cases, examining the impact of various design parameters, such as geometry and mass, on clutch performance. The study used multibody dynamic simulations and included three different designs with eight sets of parameter combinations. Andersson and Goetz (2010) performed dynamic FEA using Abaqus on the dog clutch to investigate the effect of the chamfer angle, chamfer distance, tooth angle, and axial force. He aimed to find the maximum possible engagement mismatch speed for each tooth geometry and to determine the best one. Duan (2014) developed a dynamic mathematical model for the dog teeth clutch used in automatic transmission for interlocking. The author built a Simulink model and studied the system dynamics response.

Echtler et al. (2017) analyzed the energy-saving potential of a new clutch design called TorqueLINE compared to the conventional one (MFSC) used in automatic transmissions. The study used multibody simulation to analyze different transmission architectures for relevant switching points. The results showed that TorqueLINE significantly reduces drag torques compared to the MFSC. In another paper, Mileti et al. (2019) analyzed the form-fit engagement and performance rating of six dog clutch design variants used in TorqueLINE using SIMPACK multibody simulation. They examined the successful engagement area under various axial and mismatch speeds and found that a dog clutch with a low teeth number, low flank angle, and a high angular gap has the largest successful engagement area. The simulation results were validated with experimental data.

Though the mismatch speed is an essential parameter of the gearshift process of the dog teeth clutch, the dynamics of the integrated gearshift mechanism also have a big influence. Successful dog teeth clutch shifting requires precise pairing between the mismatch speed (angular motion) and the shifting mechanism speed (axial motion). The movement of the shifting mechanism is described by a reference signal tracked by a controller.

Heavy-duty vehicles use pneumatic actuators to perform gearshifts. However, electromechanical gearbox actuators are preferred for heavy-duty EVs, as they allow more precise position control. In (Turner et al., 2007), a direct-drive electromechanical actuation system has been developed for AMT and DCT systems, and a PID controller achieves the position control of the actuator. In (Juhasz et al., 2020), different control algorithms are designed to achieve the position control of an electromechanical shift actuator. Then, the results concerning shift time and real-time applicability are compared. While electromechanical actuators have several advantages, the torsional vibrations and high-speed collisions in the case of failed gear shifts are crucial regarding the expected lifetime of the electromechanical actuator system. Hence, finding accurate shiftability conditions and shifting strategies becomes critical.

In our previous work, we introduced a kinematic model for the dog clutch shiftability and obtained a condition for a successful gearshift, called the shiftability condition, that guarantees an impact-free gearshift process (Aljawabrah and Lovas, 2023b). This work distinguishes between successful and unsuccessful gearshift events, providing a reference signal for a successful gearshift, as will be described in Chapter 3. In another work, we developed a dynamic model for a disk-type cam follower mechanism (Aljawabrah and Lovas, 2022). The used gearbox employs an electromechanical mechanism to control the linear motion of the sliding dog clutch, as will be explained later in Chapter 4. The developed dynamic system is highly nonlinear. Also, in (Aljawabrah and Lovas, 2023a), we developed a dynamic model for the

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dog clutch engagement process, dividing the engagement process into four discrete stages and modelling each stage's dynamics. The discrete stages were integrated into one continuous hybrid automata (HA) model to obtain the trajectories of the continuous states. Three gearshift cases are considered to verify the HA model, and Simulink simulation showed that the HA model could capture the continuous states' dynamics inside each discrete stage. These previously mentioned works provide the plant for the system discussed in this paper.

In this paper, we intend to solve a known problem, explained in Chapter 3, for a motorcycle transmission, described in Chapters 2 and 4. This transmission employs dog clutches as gearshifting elements and an electromechanical actuator. The research aims to develop a motion controller that guarantees a face-impact-free (scratching-free) gearshift process. We intend to apply a closed-loop control system that requires a reference signal and a plant where the control action is applied.

The steps of the reasoning are the following:

- Our work on dog clutch kinematics (Aljawabrah and Lovas, 2023b) determines optimal gearshift process parameters at given operating conditions.
- Based on the identified optimal parameters and our work for modelling the shifting mechanism dynamics (Aljawabrah and Lovas, 2022) and the process dynamics for dog clutch engagement (Aljawabrah and Lovas, 2023a), a gearshift algorithm based on the shiftability condition is developed, as well as a controller to control the gear shifting mechanism motion. Simulation results are presented and discussed.

Nomenclature

Symbol	Quantity	Symbol	Quantity	Symbol	Quantity
ξ	Clutch relative angular position	ξ_0	the initial relative angular position	R	electric motor resistance
$\Delta\omega$	mismatch speed	ϕ	angular pitch	i	electric motor current
x_0	axial gap	x_{fed}	overlap distance	K_t	torque constant
v_0	mean linear (axial) velocity	r	the mean radius of the dog clutch	Q	weight on the state error
Z	tooth number	h_t	tooth height	b_{visc}	viscous friction coefficient
ϕ_t	angular tooth thickness	Φ_b	angular backlash	$z_{i,max}$	maximum acceptable error of i^{th} state
x_s	linear position of the sliding sleeve	x_s^*	linear position reference trajectory	L	electric motor inductance
θ	Disk angular position	t	time	V	input voltage
d	damping coefficient	k	stiffness coefficient	K_e	back electromotive force constant
m	mass of the shifting mechanism	J	inertia	R	weight on the input
x	continuous state variables' vector	F_{act}	actuator force	K	state-feedback control gain
T_c	side (tangential) impact torque	F_c	front (axial) impact force	$u_{j,max}$	maximum acceptable value of j^{th} input
			Subscripts		
g	meshing gear (input side)	s	sliding sleeve (output side)	k	disk
s,i	initial linear position	s,f	final linear position	M	electric motor
s,0	linear front impact position				

2 . Presentation of the system

A dog clutch, Figure 1a, is a coupling used to transmit power. It consists of two parts having complementary geometry. These complementary shapes are referred to as dog teeth. The dog teeth can be either on an axial annular

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surface (axial dog) or a cylindrical surface (radial dog or spline). The equations describing the teeth engagement are identical for both dog teeth positions. In the following, we consider axial dog teeth only.

The main dog clutch system parameters, shown in Figure 1b and c, are the following: initial relative angular position ξ_0, mismatch speed $\Delta\omega_0$, axial velocity v_0, axial gap x_0, overlap distance x_{fed}, teeth number Z, and the angular backlash Φ_b.

The axial motion of the sliding sleeve realizes the dog clutch engagement. At the beginning of the shifting (Figure 1), the sliding sleeve moves axially with a mean axial velocity of v_0 until the axial gap is crossed (Figure 1e). We suppose a successful engagement happens when an overlap x_{fed} is reached in the axial direction without face impact (Figure 1f). After the overlap is covered (end of stage 2), several side (tangential) impacts occur between the teeth sides, either at the end of the tangential gap (Figure 1f) or at the start of this gap when the marked black teeth come into contact. The gear will bounce back and forth between these two positions until the mismatch speed is synchronized (equals 0).

Earlier research (Aljawabrah and Lovas, 2023b) has allowed us to develop the shiftability condition described by a double inequality. If the inequality (1)is fulfilled, then the shifting is possible:

$$0 \leq mod\ \left(\xi_0 + \Delta\omega_0 \frac{x_0}{v_0}, \frac{2\pi}{z}\right) \leq \Phi_b - \Delta\omega_0 \frac{x_{fed}}{v_0} \tag{1}$$

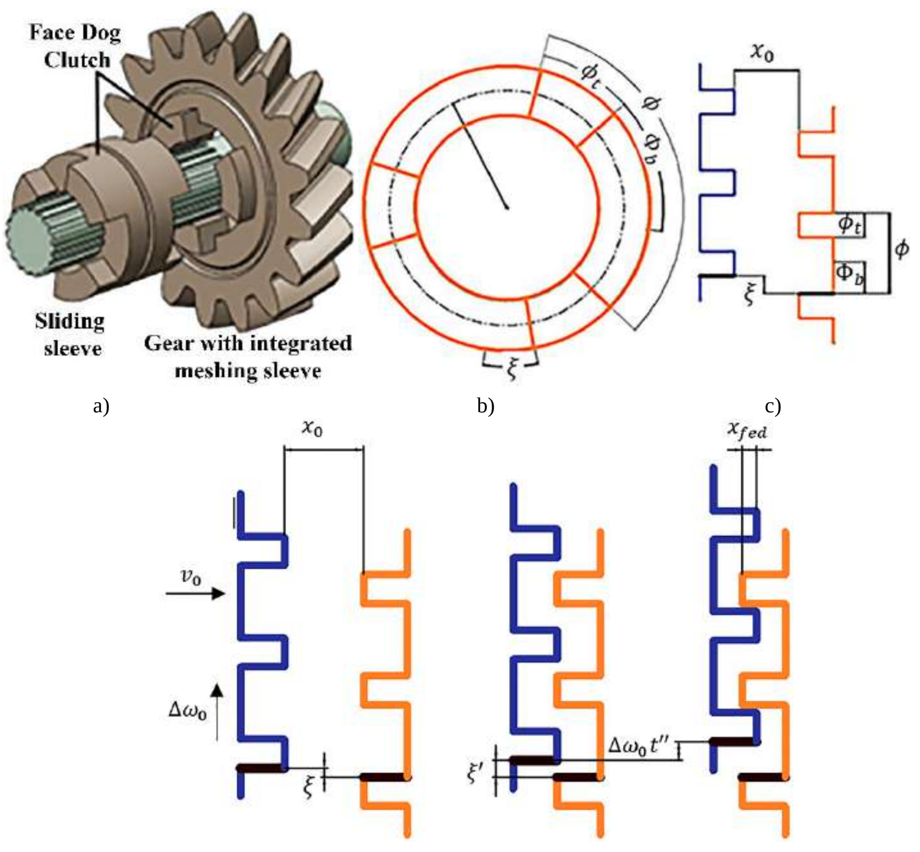

Figure 1. **Dog clutch system, a) 3D model and a 2D schematic in a) linear representation, and b) angular representation, d), e), and f) are the engagement stages.**

The gearbox that contains the dog clutch is that of an oldtimer motorbike. It has four speeds. This gearbox has the advantage of using both axial and radial dog clutches. Moreover, it has a well-known shifting problem for the 1-2 shift.

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This shifting can happen only at small angular velocity differences, as it scratches and does not shift at higher velocity difference values. Further on, the axis of its shifting element, the disk, reaches the outside of the casing, so it is easy to operate it from the outside. Thus, using this gearbox, we can:

- test the fitness of our shifting algorithm,
- test both axial and radial dog teeth
- apply an external actuator easily.

Note that in the case of motorbike gearboxes, it is common to use one common slotted element (disc, cylinder, disc sector) to guide the position of the individual shifting forks.

The shifting mechanism (Figure 2) consists of a shifting motor, a disk-type cam-follower mechanism, and two shifting forks. One fork engages the 1st and 2nd gears and the other the 3rd and 4th gears. The linear position of the forks can be at *0 mm* (neutral position), *7 mm*, or *-7 mm* as an extreme position where a specific gear will be engaged. A more detailed description of the mechanism and its motion is introduced in Chapter 4.

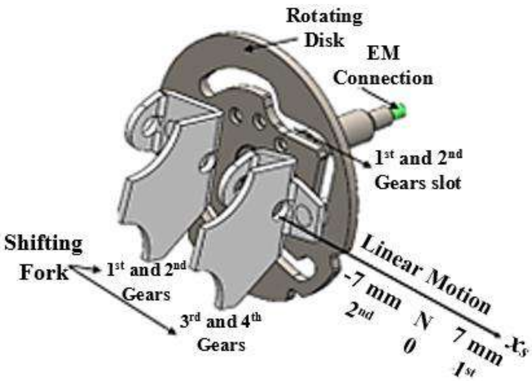

Figure 2. **Shifting mechanism 3D model**(Aljawabrah and Lovas, 2022)

3 . Choice of the control parameters

If applying the conditions found above is considered, we must handle the behaviour of the real shifting and actuating parts.

In Eq. (1), the axial speed is considered constant. The axial speed is not constant, as the real actuator force has a non-zero ramp-up duration. Even though the velocity is not constant, Eq. (1) is still valid if the mean axial speed provided by a real actuator and applied to the sliding sleeve is equivalent to the constant speed v_0. In other words, if an axial velocity v_0 value satisfies the condition in Eq. (1), the actuator should track the reference position x_s^* subjected to Eq. (2):

$$x_s^*(t) = v_0 t \tag{2}$$

Here, Eq. (2) gives a reference signal with a ramp response. However, a real controller cannot track this perfectly shaped ramp since the system has an acceleration time till reaching the mean linear velocity v_0. For this reason, the controller shall be robust enough to perform a successful gearshift even though it does not fully track the reference signal. This robustness can be achieved from the dog clutch kinematics.

In (Aljawabrah and Lovas, 2023b), we showed that at a given initial relative position ξ_0, and for a linear velocity interval ($v_{0,min}$; $v_{0,max}$), several mean linear velocity values v_0 within this interval could satisfy the shiftability conditions at a given mismatch speed $\Delta\omega_0$. The aim is to determine the portion of the predefined interval ($v_{0,min}$; $v_{0,max}$) that can satisfy the shiftability condition upon Eq. (1) at a given initial relative position and mismatch speed. To study this, we introduce the notion of probability. The probability shows a successful gear shift's possible for a given mismatch speed

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and initial relative position within a predefined mean linear velocity interval ($v_{0,min}$; $v_{0,max}$). Let's denote the shiftability condition in Eq. (1) by *G*. The probability $P_{v0}(\xi_0, \Delta\omega_0)$ is defined according to Eq. (3):

$$P = \frac{\int_{v_{0,min}}^{v_{0,max}} G\left(x_0, x_{fed}, z, \Phi_b, \xi, \Delta\omega_0, v_0\right) dv_0}{v_{0,max} - v_{0,min}} \quad (3)$$

Let us have an example using the parameters of our motorbike gearbox, with its dog clutch parameters, shown in Table 1.

Table 1 Dog clutch parameters

Parameter	Value	Parameter	Value
x_{fed}	0.5 mm	Φ_b	34°
Z	8	r	15 mm
x_0 (N-1st)	3 mm	x_0 (1st-2nd)	10 mm
h_t	4 mm		

Eq. (3)has been plotted in Figure 3a for a mean axial velocity interval of (*5; 800*) *mm/s* and the dog clutch parameters, shown in Table 1 that undergo 1st to 2nd gearshift (x_0=*10 mm*). Since the results are periodic, the values of ξ_0 have been restricted to be within the interval of (*0*; ϕ), here (*0*; *45°*).

Figure 3a shows that at lower ξ_0 values, the maximum probability decreases as the mismatch speed increases. This behaviour is similar to Bóka's model for shiftings at low rpm (Bóka et al., 2010b). Moreover, the maximum probability decreases with the initial mismatch speed. At *50 RPM*, ξ_0^{max} is *42°*, and *94%* of this interval can guarantee a successful gearshift. Then, at *300 RPM*, ξ_0^{max} is *22°*, and the probability drops to 77*%*. A red dashed line can be drawn using the probability peaks, showing the trend for the optimal initial relative position ξ_0^{max} for different mismatch speeds.

Figure 3b shows another representation. Here, the ξ_0^{max} values are shown at different mismatch speeds for two gearshift cases: the neutral to 1st gearshift (x_0=*3 mm*) and the 1st to 2nd gearshift case (x_0=*10 mm*). It can be seen that ξ_0^{max} has a linear relationship with the mismatch speed $\Delta\omega_0$. Based on these observations, we can restrict our system so that it performs a gearshift only when the initial relative position ξ_0 is at ξ_0^{max} at the operating mismatch speed, independently from the moment of the formation of the gearshift order. This assumes the highest shifting probability for the given mismatch speed.

Further, we showed that for a given mismatch speed $\Delta\omega_0$ and initial relative position, there are split continuous bands of the mean axial velocity within the interval ($v_{0,min}$; $v_{0,max}$), resulting in a successful gearshift. To illustrate this, the shiftability condition *G* (Eq. (1) has been evaluated at an initial relative position ξ_0^{max} =*30°*, and a mismatch speed $\Delta\omega_0$=*200 RPM*, at different mean axial velocities v_0 within the interval (5; 800) *mm/s*. The results in Figure 4a show various split continuous bands where *G=1*. For instance, between v_0=*250 mm/s* and *800 mm/s*, a continuous band of mean velocity values can result in a successful gearshift. Also, it shows that the bands are narrow at lower mean velocity values, but their width increases at higher mean velocity. We aim to find the most extended continuous band at the operating mismatch speed.

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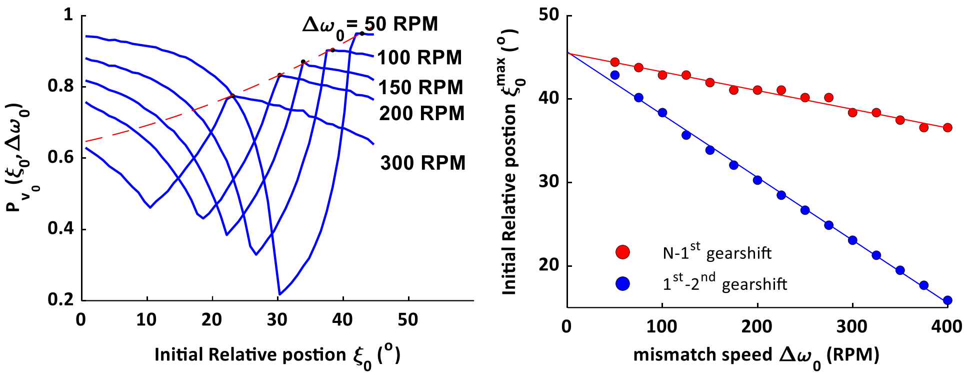
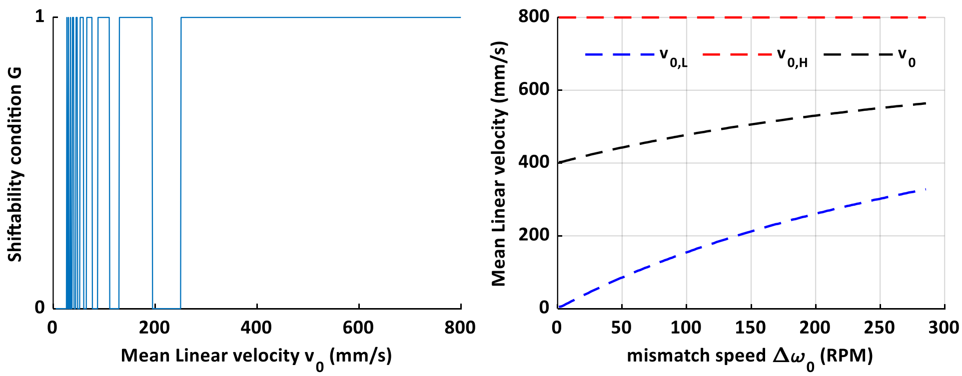


a) b)

Figure 3. a) **Shifting probability variation depending on the initial relative position, and b) Mismatch speed influence on the optimal initial relative position ξ0max**



a) b)

Figure 4. **a) Continuous bands for mean linear velocity with ξ_{0max} =30o, and $\Delta\omega_0$=200 RPM, and b) Lower and higher mean velocities for the longest continuous band at ξ_{0max} in Figure 2b**

The existence of these bands grants the controller robustness, and as the band is longer, the controller is more robust. Let us call the velocity at the lower end of the band by $v_{0,L,}$ and the velocity at the higher end by $v_{0,H}$. The goal is to find the most extended continuous band with $G=1$. This will gain the controller's robustness and improve performance, as illustrated later.

To examine the longest continuous band at different mismatch speeds $\Delta\omega_0$ with their corresponding ξ_0^{max} values, Figure 4b shows the $v_{0,L}$, $v_{0,H}$, and their average value v_0. It shows that the width of the longest band decreases with a higher mismatch speed while v_0 increases. V_0 value is governed by the mismatch speed and the maximal mean velocity $v_{0,max}$ of the defined interval ($v_{0,min}$; $v_{0,max}$). So, for the same system, a higher $v_{0,max}$ can result in a higher v_0.

Based on these mean velocity values, three different reference positions can be generated according to Eq. (2). These reference positions are x_s^*, $x_s^{*,L}$, and $x_s^{*,H}$ generated with v_0, $v_{0,L}$, and $v_{0,H,}$ respectively. For instance, from Figure 4b, at a mismatch speed of *150 RPM*, $v_{0,L}$, $v_{0,H}$, and v_0 are *230, 800*, and *515 mm/s*, respectively. The obtained x_s^*, $x_s^{*,L}$, and $x_s^{*,H}$ reference positions are shown in Figure 5. The controller is imposed to follow x_s^*. However, it can not follow this function due to the system dynamics since the real system has inertia, and the velocity reaches the prescribed value with a ramp, starting from zero. Meanwhile, if the actual position x_s lies between $x_s^{*,L}$, and $x_s^{*,H}$ at the impact position $x_{s,0}$, which is *3 mm* in this case, the controller can successfully perform a gearshift without front impact. In other words, the controller completes the task if:

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$$\frac{x_0}{v_{0,H}} \leq t(x_{s,0}) \leq \frac{x_0}{v_{0,L}} \tag{4}$$

The controller is more robust if this time window is wider at the impact position $x_{s,0}$.

As the reference trajectory x_s^* required for the successful shifting has been determined, the next step is to model the shifting mechanism dynamics and develop the controller.

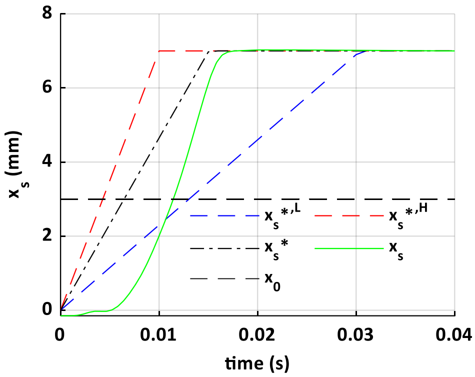

Figure 5. **Reference position x_s* and real actuator path x_s**

However, before introducing the dynamic models, a brief introduction about the gearshift strategy and vehicle velocity path is needed. The vehicle transmission contains several gear ratios, and the gearshift depends on several factors. Usually, the gearshift depends on the road conditions and the drive mode, and there are two strategies for gearshift: fuel economy mode and sport mode. Figure 6 utilizes our considered transmission to show two vehicle speed paths during gear upshift. The gearshift occurs at a lower engine speed in fuel economy mode (path 1). In sport mode, the gearshift occurs at a high engine speed (path 2). Figure 6 shows that the vehicle speed remains constant during the gearshift, but the engine speed steps down due to the gear ratio step. It also shows that the engine speed difference at the gearshift between two successive gear ratios is lower for path 1 than for path 2. The mismatch speed is directly related to the step in engine speed during the gearshift process, and the largest mismatch speed appears between the 1st and 2nd gearshift. In fact, transmission is considered to have a known problem between the 1st and 2nd gearshifts, where many face impacts occur, and the sliding sleeve hardly engages due to the high mismatch speed.

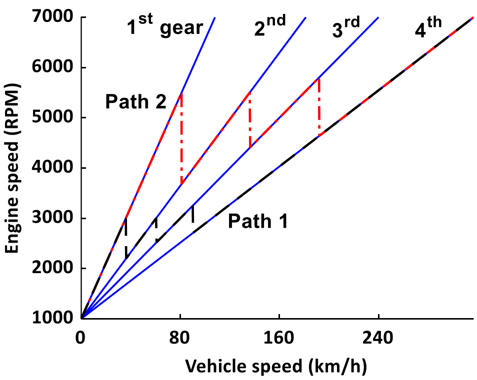

Figure 6. **Gearshift and vehicle speed path**

This work attempts to solve this problem through an impact-free gearshift, even though a large mismatch speed is present.

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The kinematics analysis introduced the shiftability condition (Aljawabrah and Lovas, 2023b), and based on this, the shift mechanism's reference trajectory has been identified. The following chapter intends to complete the path of the dog clutch analysis by looking at the system from a dynamic point of view. In the next two sections, the system dynamics is summarized based on our work in (Aljawabrah and Lovas, 2022) and (Aljawabrah and Lovas, 2023a), and then the controller development is introduced.

4 . Dynamics of the shifting mechanism and the dog clutch

As mentioned in the introduction, the transmission has four speeds, employs dog clutches as shifting elements and has an electromechanical gearshift mechanism. The rotational motion of the slotted disk is supplied by a 24 V electric motor directly connected to the disk. This paper focuses on the slot path engaging the 1st and 2nd gears. It consists of eleven parts: straight lines and circular arcs. At neutral gear, the sliding sleeve is at *0 mm,* and then it moves to *7 mm* to engage the first gear, and then it moves back to *-7 mm* to engage the second gear. The produced linear displacement will be a piecewise function of the disk (or electric motor) rotation angle (θ_K). For simplicity, we approximated the piecewise profile by a Fourier series of eight terms, as shown in Eq. (5) (Aljawabrah and Lovas, 2022), and the goodness of the fit is shown in Figure 7.

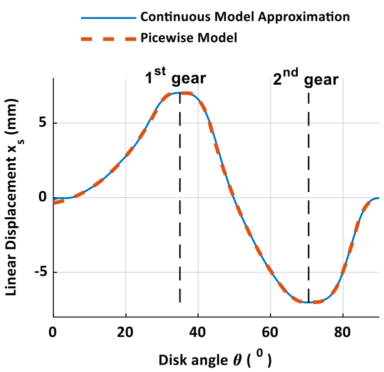

Figure 7. **Linear displacement x^s of the shifting fork depending on the disk angle** (Aljawabrah and Lovas, 2022)

Based on our dynamic modeling for the shifting mechanism (Aljawabrah and Lovas, 2022), the shifting mechanism is governed by Eq.(6) and Eq. (7). The electromechanical mechanism's parameters are listed in

Table 2.

$$x_s = a_0 + \sum_1^8 (a_k\, cos(k\omega\theta_k) + b_k\, sin(k\omega\theta_k)) \tag{5}$$

$$L\frac{di}{dt} + Ri = V - K_e\dot{\theta}_k \tag{6}$$

$$\left(m\left(\frac{dx_s}{d\theta_k}\right)^2 + J_k + J_M\right)\ddot{\theta}_k + m\frac{dx_s}{d\theta_k}\frac{d^2x_s}{d\theta_k{}^2}\dot{\theta}_k{}^2 + F_c\frac{dx_s}{d\theta_k} = K_t i \tag{7}$$

The equivalent inertia is shown in Eq. (8). It is obvious that the system has time-dependent inertia, which is a consequence of the nonlinear relationship between the linear and rotational motion.

$$J_{eq} = m\left(\frac{dx_s}{d\theta_k}\right)^2 + J_k + J_M \tag{8}$$

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Table 2 Electromechanical mechanism parameters

Parameter	Value	Parameter	Value
		Mechanical part	
m	0.6 kg	J_k	22.4×10^{-8} kg.m^2
x_0	3 mm		
		Electric Motor	
R	0.9 Ω	K_t	0.1125 N.m/A
L	3.2 mH	K_e	0.191 V.s/rad
J_M	720×10^{-9} kg.m^2		

We consider an impact-free gearshift process, so the impact force is set to zero in Eq.(7) during the control design. The system has three states Disk angle θ_k, disk speed $\dot{\theta}_k$, and motor current I, and they are referred to as x_1,x_2, and x_3, respectively. The system state vector is $\boldsymbol{x}$ while its input $\boldsymbol{u}$ is the motor voltage V. Using the Jacobian, the system equations, Eq.(6) and (7), can be linearized at a state vector $\boldsymbol{x}_k$. The state-space matrices are shown in Eq. (9) (Aljawabrah and Lovas, 2022).

$$\boldsymbol{A} = \begin{bmatrix} 0 & 1 & 0 \\ -\frac{A_{211}}{J_{eq}} - \frac{A_{212}}{J_{eq}^2} & \frac{A_{22}}{J_{eq}} & \frac{K_t}{J_{eq}} \\ 0 & -\frac{K_e}{L} & -\frac{R}{L} \end{bmatrix}$$
$$\boldsymbol{B} = [0\ 0\ 1/L\ ]^T$$
$$\boldsymbol{C} = [1\ 0\ 0] \tag{9}$$
$$\boldsymbol{D} = 0$$
$$A_{211} = m{x_2}^2\left(\left(\frac{d^2x_s}{{dx_1}^2}\right)^2 + \frac{d^3x_s}{{dx_1}^3}\frac{dx_s}{dx_1}\right)$$
$$A_{212} = 2m\left(K_t x_3 - m{x_2}^2\frac{d^2x_s}{{dx_1}^2}\frac{dx_s}{dx_1}\right)\frac{d^2x_s}{{dx_1}^2}\frac{dx_s}{dx_1}$$
$$A_{22} = 2\,mx_2\frac{dx_s}{dx_1}\frac{d^2x_s}{{dx_1}^2}$$

Now, let us consider the rotational dynamics of the dog clutch inside the gearbox. In (Aljawabrah and Lovas, 2023a), we described a detailed model for the rotational dynamics. We summarize here the important parts related to the control design, considering the face impact-free engagement process. The rotational dynamics model during the free fly phase, stage 1 (Figure 1d), is presented in Eq. (10), and Eq. (11):

$$J_g\ddot{\theta}_g = 0 \tag{10}$$

$$J_s\ddot{\theta}_s = 0 \tag{11}$$

Here, losses are neglected.

At the end of stage 2, when the system reaches the overlap distance (Figure 1f), the sliding sleeve enters stage 3. Several tangential side impacts occur during this stage, resulting in the mismatch speed synchronization. The side impact torque is given in Eq. (12), and the rotational dynamics are shown in Eq. (13)(13) and (14). Here, ξ'^{0} is the angular position for the side impact.

$$T_c = \begin{cases} k_t(\xi' - \xi'^{0}) + d_t\Delta\omega & \text{if} \quad \Phi_b \le \xi'^{+} \le \phi \\ 0 & elsewhere \end{cases} \tag{12}$$

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$$J_s\ddot{\theta}_s = T_c \quad (13)$$
$$J_g\ddot{\theta}_g = -T_c \quad (14)$$

5 . Control development

Eq. (9) shows that the state-space representation describing the shifting mechanism's behaviour is a Linear Time-Varying (LTV) model. By selecting an appropriate scheduling parameter vector (ρ), the system can be modelled using the grid-based Linear Parameter Varying (LPV) framework:

$$\dot{x}(t) = A(\rho(t))x(t) + Bu(t) \quad (15)$$

$$\rho(t) = \left[x_2(t) \quad x_3(t) \quad \frac{dx_s(t)}{dx_1(t)} \quad \frac{d^2x_s(t)}{dx_1{}^2(t)} \quad \frac{d^3x_s(t)}{dx_1{}^3(t)} \right] \quad (16)$$

In the literature, LPV systems are often controlled by high-complexity algorithms such as LPV-H∞ (Cui et al., 2015) and adaptive MPC (Lee et al., 2017). Such algorithms have exceptional performance but cannot be effectively used in embedded environments due to their high calculation cost. Linear algorithms can also control nonlinear systems by utilizing linearization, gain-scheduling techniques, and cascaded control structures (Prasad et al., 2011). In the presented case, the gear shift is successful if the face dog clutch is reached within the time window defined by the shiftability band. Thus, tracking accuracy is not crucial, and the reference position can be defined freely to a value within the shiftability band. A ramp function is used to generate continuous reference positions to simplify the control design. If the ramp gradient is chosen as the mean of $v_{0,min}$, and $v_{0,max}$, then the controller's response time can be relatively high, and minor overshoots are also acceptable in the free-fly zone. Thus, there is no need for advanced control techniques, and linear control algorithms can be sufficient. Grid-based LPV models divide the domain of scheduling parameters into a grid and describe the system's behaviour at each grid point using a Linear Time Invariant (LTI) model. Hence, a nominal LTI model must be chosen to use linear control techniques, which can be utilized for controller design.

The reference signal is obtained for the control by checking the dog clutch's relative angular position. The gearshift process can start only if the relative position ξ equals ξ_0^{max}. At time t_0, ξ reaches ξ_0^{max}, and the controller registers both the current mismatch speed $\Delta\omega(t_0)$ as initial mismatch speed $\Delta\omega_0$, and the initial relative position ξ_0 as ξ_0^{max}.

Since $\Delta\omega_0 = \Delta\omega(t_0)$, $\xi_0 = \xi_0^{max}$, and the mean linear velocity interval $(v_{0,min};\ v_{0,max})$ are known, $v_{0,L}$, and $v_{0,H}$ are determined based on Eq. (1) and v_0 is calculated according to:

$$v_0 = \frac{v_{0,L} + v_{0,H}}{2} \quad (17)$$

We assume a gearshift order arrives at *0 s*, then ξ reaches ξ_0^{max} at t_0. According to this, the reference signal $x_s^*(t)$ is:

$$x_s{}^*(t) = \begin{cases} x_{s,i} & t < t_0 \\ x_{s,i} \pm v_0(t - t_0) & t_0 \le t \le \dfrac{x_0}{v_0} + t_0 \\ x_{s,f}{}^* & t > \dfrac{x_0}{v_0} + t_0 \end{cases} \quad (18)$$

The generated reference signal is the linear position of the shifting sleeve, but the controller is designed based on the disk angle θ_k. So, the current reference linear position $x_s^*(t)$ is mapped to its corresponding disk angle $\theta_k^*(t)$ using Eq. (5). The gearshift process is summarized in Figure 8. At time *0s,* a gearshift order arrives, and the system registers $\Delta\omega(0)$ as $\Delta\omega_0$, and an array containing the $\Delta\omega_0$ and ξ_0^{max} pairs is stored within the system so that the system can identify ξ_0^{max}, given $\Delta\omega_0$. The system does request any motion but waits until $\xi_0 = \xi_0^{max}$ and registers ξ_0^{max} as ξ_0. The mean linear velocity interval $(v_{0,min};\ v_{0,max})$ is predefined within the system, and for ease of calculations, this continuous interval is discretized with *1 mm/s* step, so the continuous interval is converted to a vector with equally spaced elements, *1 mm/s* step. This vector, $\Delta\omega_0$, and ξ_0 are passed to the shiftability condition in Eq. (1), which results in a vector containing zeros and ones, and its length equals the mean linear velocity vector's length. The system identifies the largest number of

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successive elements equal to 1, which is identical to the longest band in Figure 4a. Based on this $v_{0,L}$, and $v_{0,H}$ are determined. Afterward, v_0 is calculated according to Eq. (17), and the system requests a position according to Eq. (18). Here, the role of the controller comes to force the actuator to follow the requested position.

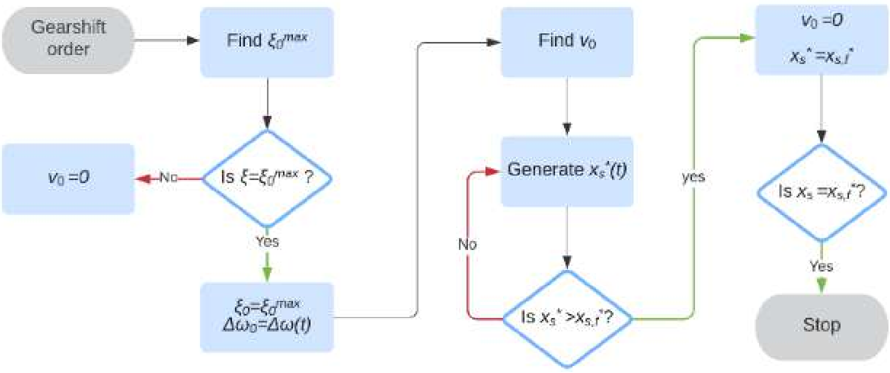

Figure 8. **Gearshift process flowchart**

By Selecting the nominal LTI model at the $\rho(t) = \vec{0}$ grid point, the nonlinear elements (e.g., the inertia, load torque) have been omitted or simplified, which leads to the well-known state-space matrix of DC motors:

$$A_{ctrl} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -\frac{b_{visc}}{J} & \frac{K_t}{J} \\ 0 & -\frac{K_e}{L} & -\frac{R}{L} \end{bmatrix} \tag{19}$$

Using the simplified state-space representation, a Linear Quadratic Regulator has been developed. The LQR control synthesis aims to find a controller, which minimizes the following quadratic cost function:

$$J(u) = \int_0^{\infty} (x^T Q x + u^T R u) dt \tag{20}$$

Then the optimal feedback law, which minimizes the value of the cost, is written as follows:

$$u = -Kx \tag{21}$$

To meet the design requirements and find an appropriate state-feedback controller, the initial weights of the cost function have been chosen using Bryson's rule:

$$Q_{ii} = \frac{1}{z_{i,max}^2} \tag{22}$$

$$R_{ii} = \frac{1}{u_{i,max}^2} \tag{23}$$

Then, they have been finetuned using heuristic methods to achieve the desired performance.

The last step of the controller design is calculating the precompensation gain (N). As LQR is a full-state feedback controller, the reference signal must be compensated by considering all the desired steady-state values. The schematic of the closed-loop system is shown in Figure 9.

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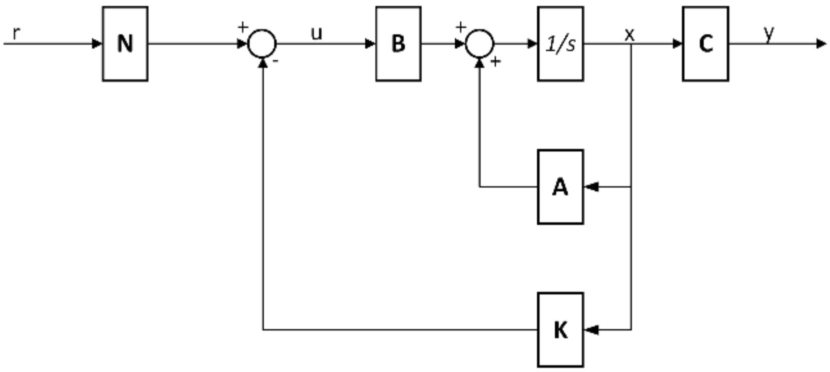

Figure 9. **Schematic layout of the closed-loop system**

6 . Simulation results and discussion

6.1 . Electric motor and shifting disk simulation

The shifting mechanism has been separately simulated on Simulink to study its nonlinear behaviour and shows the system's open-loop response. 5 V constant supply tension was supposed. Several time points in this figure are discussed, and for ease of interpretation, these key time points are named using Latin numbers and shown in the figure. The essential key time points for each subfigure are shown. The same procedure will be used in the following figures.

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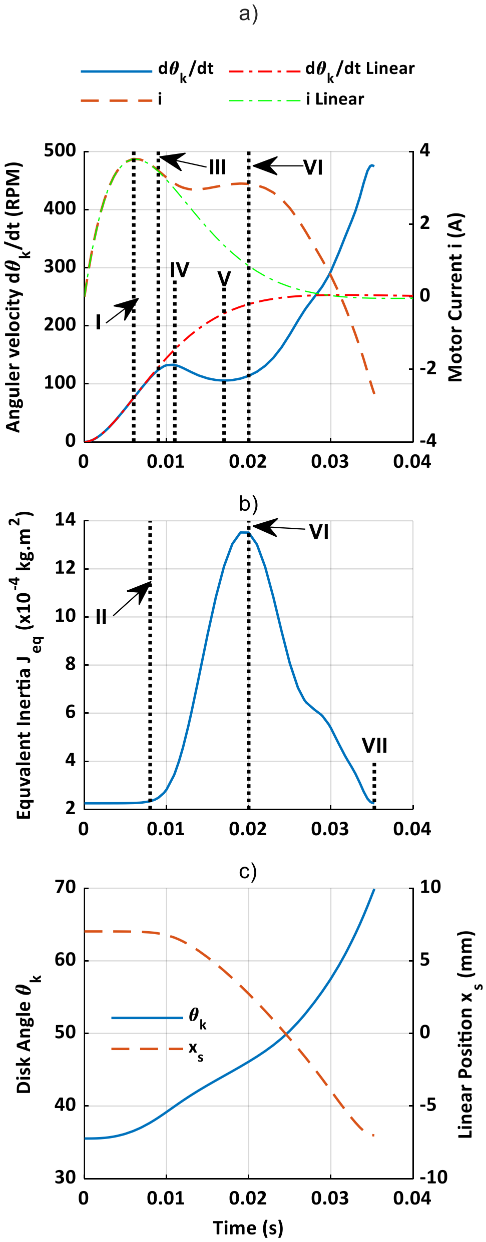

Figure 10 **1st to 2nd gear shift open-loop response without front impact for a) angular speed and motor current, b) equivalent inertia, and c) disk (motor) angle and sliding sleeve linear position. Key time points: I: 0.006s, II: 0.008s, III: 0.009s, IV: 0.011s, V: 0.017s, VI: 0.02s, VII: 0.035s.**

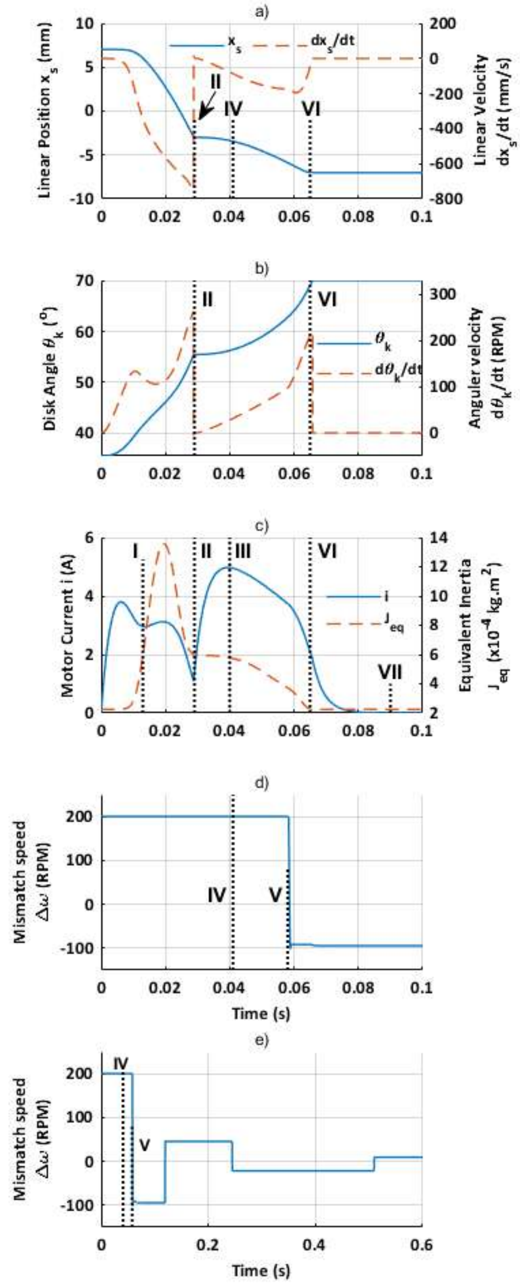

Figure 11. **1st to 2nd gear shift open-loop response for a) sleeve's linear position and speed, b) disk angle and angular speed, c) motor current and equivalent inertia, and d) Mismatch speed. Key time points: I: 0.013 s, II: 0.029 s, III: 0.04 s, IV: 0.041 s, V: 0.058 s, VI: 0.065 s and VII: 0.09 s.**

In Figure 10a, the motor angular velocity increases until time point IV, *0.011 s*, and then decreases until time point V, *0.017 s*, because of the increased inertia, shown in Figure 10b. The inertia does not change before time point II, *0.008 s*, and the motor angular velocity can increase. Then the inertia rises rapidly, and the motor velocity decreases from *0.011 s*. Further on, the inertia decreases rapidly from time point VI, *0.02 s*, and the motor velocity increases rapidly

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from $0.017\ s$. Figure 10a shows that the increasing motor velocity decreases motor current from $0.02\ s$ due to an increasing back electromotive force.

As the inertia does not change before $0.008\ s$, Figure 10a shows that the system follows a similar behaviour to a linear system before time point III, $0.009\ s$, which can be obtained by setting the mass m in Eq. (7) to zero. The linear system has a maximum current of $3.8\ A$ at time point I, $0.006\ s$ when the motor angular velocity is $76\ RPM$. Beyond this time, the motor velocity increases, and the motor current decreases.

The linear system has a steady-state motor velocity of $250\ RPM$ when the back electromotive force balances the input voltage, while our nonlinear system can reach $475\ RPM$ (Figure 10a). The system has time-varying inertia, and when the inertia increases, the system stores energy. When the inertia decreases, the stored energy is transferred to the constant inertia part: the motor and disk inertia. This effect is seen in Figure 10a beyond $0.02s$. From Figure 10b, the system has $0.0014\ kg.m^2$ inertia at $0.02\ s$, but it falls to $0.0002\ kg.m^2$ at time point VII, $0.035\ s$, to one-seventh of the maximum value.

6.2 . Full system shifting simulation without control.

In what follows, the shifting mechanism model has been integrated with the dog clutch dynamics model. The model shows the system's behaviour in the presence of a front impact force F_c, under $5\ V$ constant input voltage. Figure 11 shows the system response for the 1st to 2nd gearshift with an initial relative position ξ_0 of 9^o (0.2ϕ) and an initial mismatch speed of $200\ RPM$.

In Figure 11a, the sliding sleeve starts at *7 mm, and* then freely moves until it hits the gear at $-3\ mm$, at the time point II, $0.029\ s$. It stops briefly until the next tangential gap passes, then moves until it reaches the final position of $-7\ mm$. Before $0.029\ s$, the system response in Figure 11 is similar to that in Figure 10 for the corresponding quantities since both cases have no impact.

At time point II, $0.029\ s$, and time point I, $0.013\ s$, the system has the same inertia value as Figure 11c shows. However, Figure 11b shows that the system has higher angular acceleration at $0.013s$ than at $0.029s$ and a higher current at $0.013s$, as Figure 11c shows.

When a teeth front impact happens, the linear velocity and the angular velocity fall to zero, as shown in Figure 11a and Figure 11b, but the current increases rapidly due to the absence of the back electromotive force. Figure 11c shows that the current was ramping up towards its theoretical peak value of $5.6\ A$, when the shifting mechanism is at rest, but it could reach only $4.8\ A$ at time point III, $0.04\ s$, since the system starts to accelerate; thus, the current decreases. At time point VI, $0.065\ s$, the sliding sleeve reaches its final position $x_{s,f}$, and the input voltage is set to zero. Note that the current drops to zero at time point VII, $0.09\ s$, due to the motor inductance.

From Figure 11a, at $0.041s$, the sliding sleeve passes to stage 2, which is the end of reaching the overlap at $-3.5\ mm$, then the first side impact occurs at time point V, $0.058s$, as Figure 11d shows. Figure 11e is an extension for Figure 11d with extended simulation time. It shows that several side impacts happen until the mismatch speed is synchronized. The inertia of the output side (the sliding sleeve side) is considered infinite compared to the input side (the meshing gear side). Thus, the angular speed of the meshing gear changes while the angular speed of the dog clutch sleeve is constant. After each side impact, the rotation of the gear is reversed, which is clearly seen in Figure 11e, where the mismatch speed is alternating around zero. The sliding sleeve needed $0.063\ s$ to reach its final linear position, but it lasted $0.51\ s$ to synchronize its angular velocity with the meshing gear.

6.3 . Shifting simulation with LQR control

In the following, an LQR controller has been added to the previously presented system, and the results are shown in Figure 12a-c. The simulation presents a neutral to 1st gear shift. The applied initial relative position ξ_0 is 9^o, while the initial mismatch speed is $310\ RPM$. The applied mean velocity interval is ($5; 800$) mm/s. Figure 12a shows the linear position, while Figure 12b shows the relative angular position ξ in the first cycle of one pitch period $(0, \phi)$ or ($0; 45^o$).

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At *310 RPM*, ξ_0^{max} is 38^o, and a gearshift order arrives at *0 s.* Figure 12a shows that the shifting process does not start until the time point I, when the relative position is ξ_0^{max}, as Figure 12b shows.

At *310 RPM*, $v_{0,L}$, $v_{0,H}$, and v_0 are *161 mm/s*, *800 mm/s*, and *481 mm/s*, respectively, where they are used to generate the limit reference signals $x_s^{*,L}$, $x_s^{*,H}$, and the reference signal x_s^* respectively. The sliding sleeve starts at *0 mm, and* then moves until it reaches its final position $x_{s,f}$ at *7 mm*. A teeth front impact can occur at a *3 mm*, but the controller can successfully closely track the reference signal. The linear position x_s LQR is between the limit reference signals $x_s^{*,L}$, and $x_s^{*,H}$ at the impact position $x_{s,0}$, so there is no front impact.

In Figure 12b, the relative angular position ξ increases from 9^o (ξ_0) until it reaches 45^o at the time point II, then drops suddenly to zero. ξ increases further, but we injected it back to the start of the period (0; 45^o) to better show the results. ξ starts to increase again from 0^o until it reaches 34^o or Φ_b at time point IV, where the first side impact occurs. After the dog clutch passes stage 2, the side impact can happen at two locations within the tangential gap, one at the end of this gap, where ξ equals Φ_b, or at the start of the gap, where ξ equals 0^o. The sliding sleeve passed stage 2 at time point III, where x_s LQR is *3.5 mm*, as Figure 12a shows. Figure 12b shows that ξ is 32^o, but the first side impact occurred later at *0.038 s* when ξ is 34^o. After this impact, the gear rotation direction is reversed, and another side impact occurred later at time point V, *0.061 s* when ξ equals 0^o, where the gear rotation direction is reversed again. This causes the relative angular position to be restricted to the backlash interval $(0; \Phi_b)$, or (0; 34^o). Actually, these side impacts continue to occur either at 0^o or Φ_b relative angular positions until the mismatch speed is synchronized and both the sliding sleeve and the gear move as one unit, where the relative angular position remains at either 0^o or Φ_b, depending on the last impact location that caused the mismatch speed to be synchronized.

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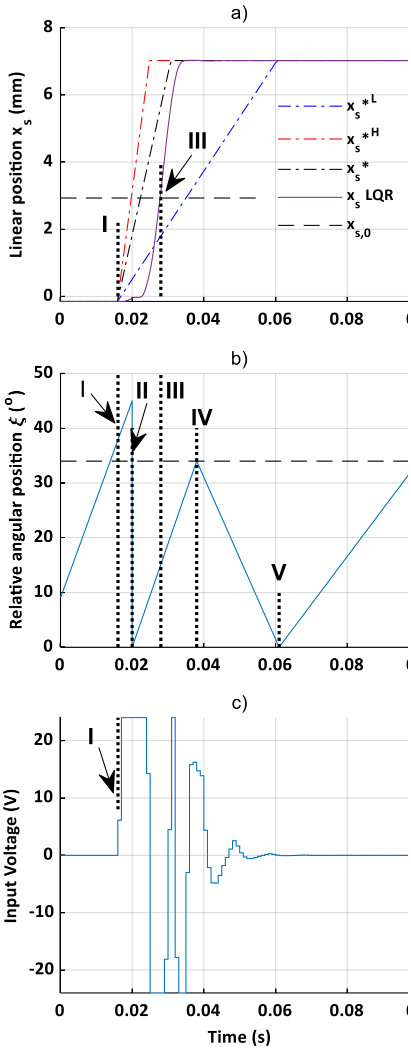

Figure 12. **Closed-loop response for N to 1st gear. Key time points: I: 0.016 s, II:0.02 s, III:0.028 s, IV:0.038 s, and V:0.061 s.**

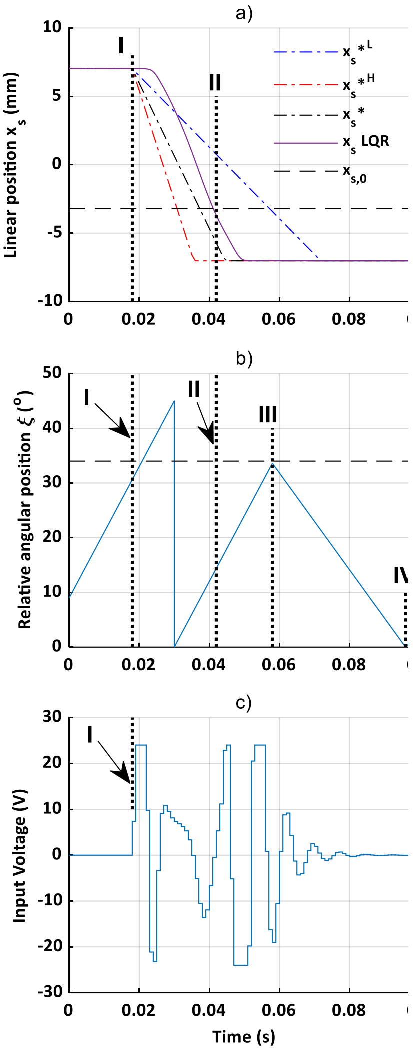

Figure 13. **Closed-loop response for 1st to 2nd gearshift. Key time points: I:0.018 s, II:0.042 s, III:0.058 s, and IV:0.096 s.**

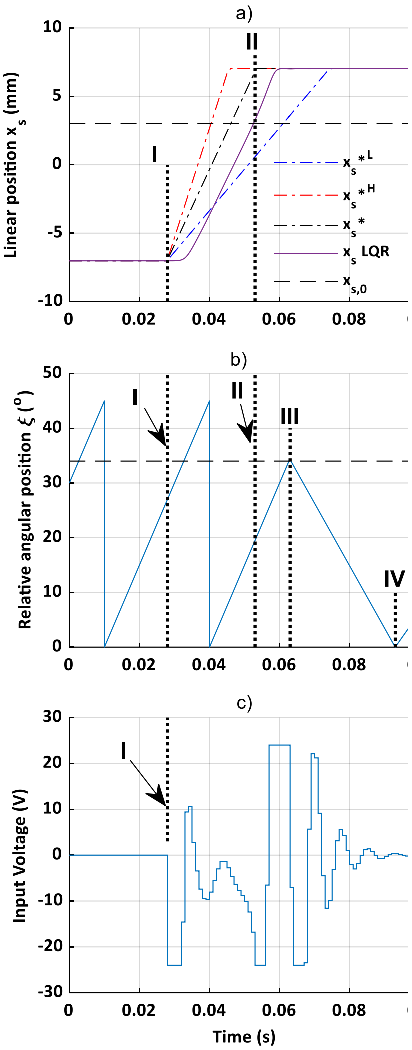

Figure 14. **Closed-loop response for 2nd to 1st gearshift. Key time points: I:0.028 s, II:0.053 s, III:0.063 s, and IV:0.093 s.**

A further simulation shows a 1st to 2nd gearshift. The applied initial relative position ξ_0 is *9º,* while the initial mismatch speed is *200 RPM*. The applied mean velocity interval is (*5; 800*) *mm/s*. The LQR controller has been tested; the results are shown in Figure 13a-c. At *200 RPM*, ξ_0^{max} is *30º*, and a gearshift order arrives at *0 s*. However, Figure 13a shows that the shifting process does not start until time point I, when the relative position is ξ_0^{max} , as seen in Figure 13b.

At *200 RPM*, $v_{0,L}$, $v_{0,H}$, and v_0 are *261 mm/s*, *800 mm/s*, and *531 mm/s*, respectively, and they are used to generate the limit reference signals $x_s^{*,L}$, $x_s^{*,H}$, and the reference signal x_s^* respectively. The sliding sleeve starts at *7 mm*, and then moves until it reaches its final position $x_{s,f}$ at *-7 mm*. A teeth front impact might occur at *-3 mm* linear position, but the controller can perform the gearshift process without impact.

Figure 13b shows that the first side impact occurs at time point III after the sliding sleeve has passed to stage 2. The sliding sleeve passed to stage 2 at time point II, when x_s LQR is *-3.5 mm*, as Figure 13a shows. At this time, Figure 13b shows that ξ is *15º,* but the side impact occurs at *0.058 s*, when ξ is *34º*. Later, another side impact occurs at time point IV, when ξ is 0º.

Finally, a simulation shows a 2nd to 1st gearshift. The applied initial relative position ξ_0 is $30^{o,}$ while the initial mismatch speed is *250 RPM*. The applied mean velocity interval is (*5; 800*) *mm/s*. The LQR controller has been tested; the results are shown in Figure 14a-c. At *250 RPM*, ξ_0^{max} is 28^o, and a gearshift order arrives at *0 s*. However, Figure 14a shows that the shifting process does not start until time point I, when the relative position is ξ_0^{max} , as seen in Figure 14b.

At *250 RPM*, $v_{0,L}$, $v_{0,H}$, and v_0 are *303 mm/s*, *800 mm/s*, and *552 mm/s*, respectively, and they are used to generate the limit reference signals $x_s^{*,L}$, $x_s^{*,H}$, and the reference signal x_s^* respectively. The sliding sleeve starts at *-7 mm*, and then moves until it reaches its final position $x_{s,f}$ at *7 mm*. A teeth front impact might occur at a *3 mm* linear position, but the controller can perform the gearshift process without impact.

Figure 14b shows that after the sliding sleeve has passed stage 2, the first side impact occurs at time point III. The sliding sleeve passed stage 2 at time point II, when x_s LQR is *3.5 mm*, as Figure 14a shows. At this time, Figure 14b shows ξ is $20^{o,}$ but the side impact occurs at *0.063 s* when ξ is 34^o. Later, another side impact occurs at point IV, when ξ is 0^o.

7 . Conclusion

Based on the dog clutch kinematics, the optimal relative position ξ_0^{max}, which allows the highest successful shifting probability, is determined for different mismatch speeds. ξ_0^{max} is the parameter controlling the start of the gearshift process actuation at given operating conditions. The system kinematics study provided that the velocity bands form envelopes that grant the controller robustness.

Further on, the shifting mechanism dynamics have been analyzed. A comparison between the nonlinear and linear model approach showed that the time-varying inertia, which arises from the linearly moving parts and the nonlinear linear-rotational motion relationship, significantly affects the open-loop response for the nonlinear system. The shifting mechanism dynamics were integrated with the dog clutch rotational dynamics to perform a full model simulation and check the open-loop response. The implemented system showed similar results to the shifting mechanism response but only in the zone before an eventual front impact.

The nonlinear dynamics of the shifting mechanism would require a complex controller design, but the existence of the velocity bands (the envelopes) eased the design process. A linearized version of the LPV state-space model could be derived, which led to an LTI state-space system. This LTI system is utilized to design an LQR controller. The controller has been integrated with the complete system model to check its reliability and test our approach of utilizing the velocity bands to generate the reference and limit reference signals. The controller is tested for neutral to 1st, 1st to 2nd, and 2nd to 1st gearshifts. The results showed that the LQR controller could perform a successful gearshift in both cases without front impact, even though it does not track completely the reference signal.

While this work focused on a specific transmission configuration, it can be extended to other systems using the dog clutch. The models of the kinematics, the dynamics, and the optimal reference trajectory approach remain the same. For a new controller development, the dynamics of a given actuator mechanism have to be integrated with a given dog clutch dynamics to help of development of more sustainable transmission system for vehicles.

A further step in the research will be to test the algorithm with the hardware in the loop, identify the system parameters, and check shiftability in real conditions.

References

Al-Oran, O., Lezsovits, F.Aljawabrah, A. (2020): Exergy and energy amelioration for parabolic trough collector using mono and hybrid nanofluids. *Journal of Thermal Analysis and Calorimetry*. 140(3), 1579-1596. DOI: https://doi.org/ghdrdt

Aljawabrah, A.Lovas, L. (2022): Dynamic Modeling of An Electromechanical Gearshift Actuator [in Hungarian: Elektromechanikus Sebességváltó Aktuátor Dinamikai Modellezése]. *Machines* [in Hungarian: GÉP]. 73(3-4), 19-22.

Aljawabrah, A.Lovas, L. (2023a): Dynamic Modeling of the Dog Clutch Engagement Process Using Hybrid Automata. *Jordan Journal of Mechanical and Industrial Engineering.* 17(1), 127-138. URL: https://jjmie.hu.edu.jo/vol17/vol17-1/10-JJMIE-278-22.pdf

Aljawabrah, A.Lovas, L. (2023b): Kinematical Model of The Dog Clutch Shifting [In Hungraian: Körmös Tengelykapcsoló Kapcsolás Kinematikai Modellje]. *Machines* [in Hungarian: GÉP]. 74(1), 9-12.

Alsardia, T., Lovas, L.Ficzere, P. (2021) Prototype for fit investigations. *Design Of Machines And Structures: A Publication Of The University Of Miskolc*. 11(1), 5-15.

Alzyod, H.Ficzere, P. (2021) Potential applications of additive manufacturing technologies in the vehicle industry. *Design Of Machines And Structures: A Publication Of The University Of Miskolc*. 11(2), 5-13.

Andersson, M.Goetz, K. (2010). FE analysis of a dog clutch for trucks withall-wheel-drive Graduate Thesis. Linnaeus University, Växjö. URL: https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A634202&dswid=8486.https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A634202&dswid=8486 (Downloaded: 20 September 2020)

Bóka, G., Lovas, L., Márialigeti, J.Trencséni, B. (2010a) Engagement capability of face-dog clutches on heavy duty automated mechanical transmissions with transmission brake. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*. 224(9), 1125-1139. DOI: https://doi.org/bpcw6f

Bóka, G., Márialigeti, J., Lovas, L.Trencséni, B. (2009). External synchronization strategies for automated mechanical transmissions with face dog clutch and countershaft brake. *Proceedings of the 8th International Multidisciplinary Conference*.

Bóka, G., Márialigeti, J., Lovas, L.Trencséni, B. (2010b) Face dog clutch engagement at low mismatch speed. *Periodica Polytechnica Transportation Engineering*. 38(1), 29-35. DOI: https://doi.org/nj85

Burgelman, R. A.Grove, A. S. (2010) Toward Electric Cars and Clean Coal: A Comparative Analysis of Strategies and Strategy-Making in the US and China. Research Papers 2048, Stanford University, Graduate School of Business.

Council, N. R. (2015). Cost, effectiveness, and deployment of fuel economy technologies for light-duty vehicles. National Academies Press, Washington, D.C., USA.

Cui, L., Chen, L.Duan, D. (2015) Gain-scheduling model predictive control for unmanned airship with LPV system description. *Journal of Systems Engineering and Electronics*. 26(5), 1043-1051. DOI: https://doi.org/nj86

Dick, A., Greiner, J., Locher, A.Jauch, F. (2013) Optimization potential for a state of the art 8-Speed AT. *SAE International Journal of Passenger Vehicle Systems*. 6(2013-01-1272), 899-907. DOI: https://doi.org/nj87

Duan, C. (2014) Analytical study of a dog clutch in automatic transmission application. SAE International Journal of Passenger Vehicle Systems. 7(2014-01-1775), 1155-1162. DOI: https://doi.org/gj3fvb

Echtler, P., Mileti, M.Damm, A. (2017) TorqueLine-Konische Kupplung mit Formschluss als alternatives Schaltelement für Automatikgetriebe. VDI-Fachtagung Kupplungen und Kupplungssysteme in Antrieben, Ettlingen.

Eriksson, F., Kuttikkal, J. L.Mehari, A. (2013). Parametric study of a dog clutch used in a transfer case for trucks. Graduate Thesis. Linnaeus University, Växjö. URL: https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A632773&dswid=-8516.https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A632773&dswid=-8516 (Downloaded: 22 September 2020)

Farkas, G.Lovas, L. (2014): Connectivity test of Dog Clutch [in Hungarian: Körmös Tengelykapcsoló Kapcsolhatóságának Vizsgálata]. *Machines* [in Hungarian: GÉP]. LXV.

Greiner, J.Grumbach, M. (2013) Automatic transmission systems beyond 2020-challenges and competition. *SAE Technical Paper.* 0148-7191.

Juhasz, B., Szabo, A., Becsi, T.Aradi, S. (2020). Control design of an electromechanical gearbox actuator. *Proceedings of the 2020 IEEE 24th International Conference on Intelligent Engineering Systems* (INES). 109-114.

Laird, M. P., Lawton, B., and Gregory, R.P. (1990) Dog Clutches for Rapid Gear Changes in Automotive Gearboxes. *Proceedings of the Institution of Mechanical Engineers first international conference*. 102-112.

Lee, Y., Lee, S.-H.Chung, C. C. (2017) LPV H infinity Control with Disturbance Estimation for Permanent Magnet Synchronous Motors. *IEEE Transactions on Industrial Electronics*. 65(1), 488-497. DOI: https://doi.org/gfz2f6

Liu, D., Li, S.Liu, H. (2021) Experimental Study on Formaldehyde Emission from Environmental Protection and Energy-Saving Alcohol Fuel for Vehicles. *Jordan Journal of Mechanical and Industrial Engineering*. 15(1), 1-6. URL: https://jjmie.hu.edu.jo/v15-1/01-A81050.pdf

Lovas, L., Play, D., Márialigeti, J.Rigal, J.-F. (2006a) Mechanical behaviour simulation for synchromesh mechanism improvements. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*. 220(7), 919-945. DOI: https://doi.org/c7tgp3

Lovas, L., Play, D., Márialigeti, J.Rigal, J.-F. (2006b) Modelling of gear changing behaviour. *Periodica Polytechnica Transportation Engineering.* 34(1-2), 35-58. URL: https://pp.bme.hu/tr/article/view/1898

Mallouh, M. A., Denman, B., Surgenor, B.Peppley, B. (2010) A study of fuel cell hybrid auto rickshaws using realistic urban drive cycles. *Jordan Journal of Mechanical and Industrial Engineering*. 4(1), 225-229. URL: https://jjmie.hu.edu.jo/files/v4n1%20wrong%20header/30.pdf

Mileti, M., Pointner, L., Pflaum, H.Stahl, K. (2019) TorqueLINE Cone Clutch: Performance Analysis of Highly Dynamic Form-Fit Shifts in Automatic Transmissions.) *2019 International Conference on Advanced Vehicle Powertrains*.

Milovančević, M., Milčić, D., Andjelkovic, B.Vračar, L. (2022) Train Driving Parameters Optimization to Maximize Efficiency and Fuel Consumption. *Acta Polytechnica Hungarica*. 19(3). URL: https://acta.uni-obuda.hu/Milovancevic_Milcic_Andjelkovic_Vracar_121.pdf

Nguyen, D. D., Moghaddam, H., Pirouzfar, V., Fayyazbakhsh, A.Su, C.-H. (2021) Improving the gasoline properties by blending butanol-Al2O3 to optimize the engine performance and reduce air pollution. *Energy*. 218, 119442. DOI: https://doi.org/gqhf5g

Obeidi, T., Larbes, C., Ilinca, A., Filiz, G.Kebir, T. (2018) Fuzzy logic-based maximum power point tracking for a solar electric vehicle. Acta *Polytechnica Hungarica*. 15(7), 133-156. URL: https://acta.uni-obuda.hu/Obeidi_Larbes_Ilinca_Tchoketch-Kebir_86.pdf

Prasad, L. B., Tyagi, B.Gupta, H. O. (2011). Optimal control of nonlinear inverted pendulum dynamical system with disturbance input using PID controller & LQR. *Proceedings of the 2011 IEEE International Conference on Control System, Computing and Engineering*. 540-545.

Rudolph, F., Schaefer, M., Damm, A., Metzner, F.Steinberg, I. (2007) The innovative seven speed dual clutch gearbox for Volkswagen's compact cars; Das innovative 7-Gang-Doppelkupplungsgetriebe fuer die Kompaktklasse von Volkswagen.) 28. International Vienna motor symposium.

Shiotsu, I., Tani, H., Kimura, M., Nozawa, Y., Honda, A., Tabuchi, M., Yoshino, H.Kanzaki, K. (2019) Development of High Efficiency Dog Clutch with One-Way Mechanism for Stepped Automatic Transmissions. *International Journal of Automotive Engineering*. 10(2), 156-161. URL: https://www.jstage.jst.go.jp/article/jsaeijae/10/2/10_20194098/_pdf/-char/ja

Socin, R. J.Walters, L. K. (1968) Manual transmission synchronizers. *SAE Transactions*. 77, 31-65.

Tseng, C.-Y.Yu, C.-H. (2015) Advanced shifting control of synchronizer mechanisms for clutchless automatic manual transmission in an electric vehicle. *Mechanism and Machine Theory*. 84, 37-56. URL: https://doi.org/f6rt3j

Turner, A., Ramsay, K., Clark, R.Howe, D. (2007). Direct-drive rotary-linear electromechanical actuation system for control of gearshifts in automated transmissions. *Proceedings of the 2007 IEEE Vehicle Power and Propulsion Conference*. 267-272.

Vierk, D. T.Kowal, S. J. (2018) Composite friction and dog clutch.), US Patent 10,060,485.

Walker, P. D., Fang, Y.Zhang, N. (2017) Dynamics and control of clutchless automated manual transmissions for electric vehicles. *Journal of Vibration and Acoustics*. 139(6), 061005. DOI: https://doi.org/gkgmfh

Xu, X., Dong, P., Liu, Y.Zhang, H. (2018) Progress in automotive transmission technology. *Automotive Innovation*. 1, 187-210. DOI: https://doi.org/gp4pww

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Sustainability of Maritime and Inland Ports

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Abstract

Maritime and inland ports are a cornerstone in the transport system of each state, providing different types of logistics services. In the last 80 years, they have undergone significant changes because of increased cargo volume transported by maritime and inland water transport, the transport capacity of different types of vessels, and their transport speed, and the introduction of push technology in inland navigation. Nowadays, they play a role as logistics hubs, and their activities can significantly impact the environment and local communities living close to these ports. The sustainability of ports is determined by some aspects like environmental, economic, social, and energy efficiency. This paper aims to investigate the sustainable port development. Nowadays port automatization is very important cognitive decision is needed to find the most suitable development strategies.

Keywords
sustainability, maritime and inland ports, emergency efficiency, automatization, emissions,

1. Introduction

Transport is the most crucial element in a logistics system. It connects different parts of the logistics chain. The transport of raw materials, semi-finished or finished products is carried out by moving various means of transport on the transport route from the production site to the point of composition. The downtimes that arise while transporting goods in the system door to door can be eliminated by incorporating multimodal logistics hubs in the logistics chain, providing storage, distribution of goods, and other logistics services. Each maritime and inland port can be considered as such a hub because it performs loading, unloading, transporting goods, and other functions associated with the complex services of vessels, crew, or goods.

Sustainability has become a fundamental element in the operation of modern maritime and inland ports (Maternová, Materna, Dávid, 2022). Revealing causal factors influencing sustainable and safe navigation in central Europe.

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Sustainability, 14(4), 2231.). These ports are part of the global logistics chain, playing the role of gateways for international trade and billions of goods transported by seagoing vessels on oceans or seas between the continents or inland vessels on waterways. Their activities can significantly impact the environment and local communities, which creates an imperative need for some changes in ports based on environmental, economic, and social aspects and energy efficiency. In this paper the automatization and sustainability is investigated. Our hypothesis is that there is a financial, social and environmental balance in sustainable automatization of ports.

2. Maritime and inland ports as logistics hubs

The primary role of logistics hubs is to increase the quality and efficiency of transport and manage transport flows. These hubs are typically established in places where transport flows are concentrated, essential transport routes intersect each other, and the directions of transport flows alter. Natural places for their location are economic and industrial agglomerations, transport junctions, container terminals, state borders, maritime or inland ports.

According to the establishment, multimodal logistics hubs can be divided into two groups. The first group consists of hubs that arise randomly according to the actual requirements and development of the market (most hubs are established this way). The second group consists of centers that are constructed according to a set model.

The main determinants for the location of these hubs are:

- transport routes and their capacity,
- transport infrastructure (a direct connection of the logistics hub with other modes of transport),
- the distance between the city core and the logistics hub,
- the distance between customers and the logistics hub,
- the distance between an airport/maritime or inland port and the logistics hub,
- the total area of the logistics hub and its possibilities for future development.

The disposition of the logistics hub depends on the volume of transport flows, the structure of handling products, and its infrastructure. The most important parts of logistics centers are transshipment areas and their infrastructure (handling facilities and devices, road and railway infrastructure) and storage facilities (warehouses and open storage areas).

In multimodal logistics hubs, there are concentrated:

- container terminals,
- entities that carry out transport operations (forwarders, carriers, navigation companies),
- entities that offer various services associated with cargo (custom or quality inspection, tallyman or stevedore services, special treatment of cargo)
- technical, operational, and administrative facilities associated with transport (warehouses, facilities which offer various services, for instance, supplying, repair, guard, rescue, and emergency services) (Dávid A., Sosedová, J. 2005).

2.1 History and functions

At the beginning of the 20th century, ports used to be places located on the coast of the seas, oceans (maritime ports), or waterways (inland ports) where maritime or inland water transport used to meet with other modes of transport (rail, road). Transport of cargo used to take about two-thirds of operating time and its transshipment in maritime or inland ports used to take only one-third of this time.

The situation changed after the Second World War due to the increase in cargo volume, which was transported by maritime and inland water transport, the introduction of push technology in inland navigation, and the increase of the transport capacity of different types of vessels and their speed. These factors caused the disproportion between the performance and efficiency of maritime and inland water transport and the handling facilities and devices of maritime and inland ports. Therefore, it was necessary to increase their efficiency, to enlarge port areas, and to build a new generation of maritime and inland vessels.

Maritime ports are generally located on the coasts of oceans or seas. In comparison with inland ports, they provide a larger scale of logistics services (see Figure 1), have more sophisticated handling facilities and devices used for

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transshipment cargo operations than inland ports, and are designed for different types of large seagoing vessels carrying cargo.

Nowadays, inland ports are transport hubs situated on waterways such as navigable rivers, lakes, or canals. They consist of berths, where cargo is handled by different types of cranes, stored in warehouses or open storage areas, or transported to the customers by other modes of transport. In comparison with maritime ports, they provide a smaller scale of logistics services.

An important part of each maritime and inland port is its connection with other modes of transport (road and railway transport). Railway transport carries mainly bulk cargo for longer distances between the port and the hinterland. Road transport carries mainly general cargo, including containers, and is used by companies in the vicinity of the port.

Maritime and inland ports should be designed and constructed to provide (Maternová et al., 2023:

- a fast and safe sailing of vessels from the waterway to port,
- smooth and safe maneuvering of vessels into water area, their anchoring, formation of convoys,
- a fast loading/unloading of cargo between vessels and the land of the port,
- a direct connection with other modes of transport.

A lot of factors influence the location of maritime and inland ports. Due to economic reasons, ports are generally situated near industrial and commercial centers. The topography of the site and its geological structure are very important factors for the construction of a new port. Additionally, the total area of the port and its surroundings are important for the location of basins, berths, handling and storage facilities (cranes, warehouse), infrastructure (roads and railways), and other buildings that are required for the operation of maritime or inland port (Dávid, 2023).

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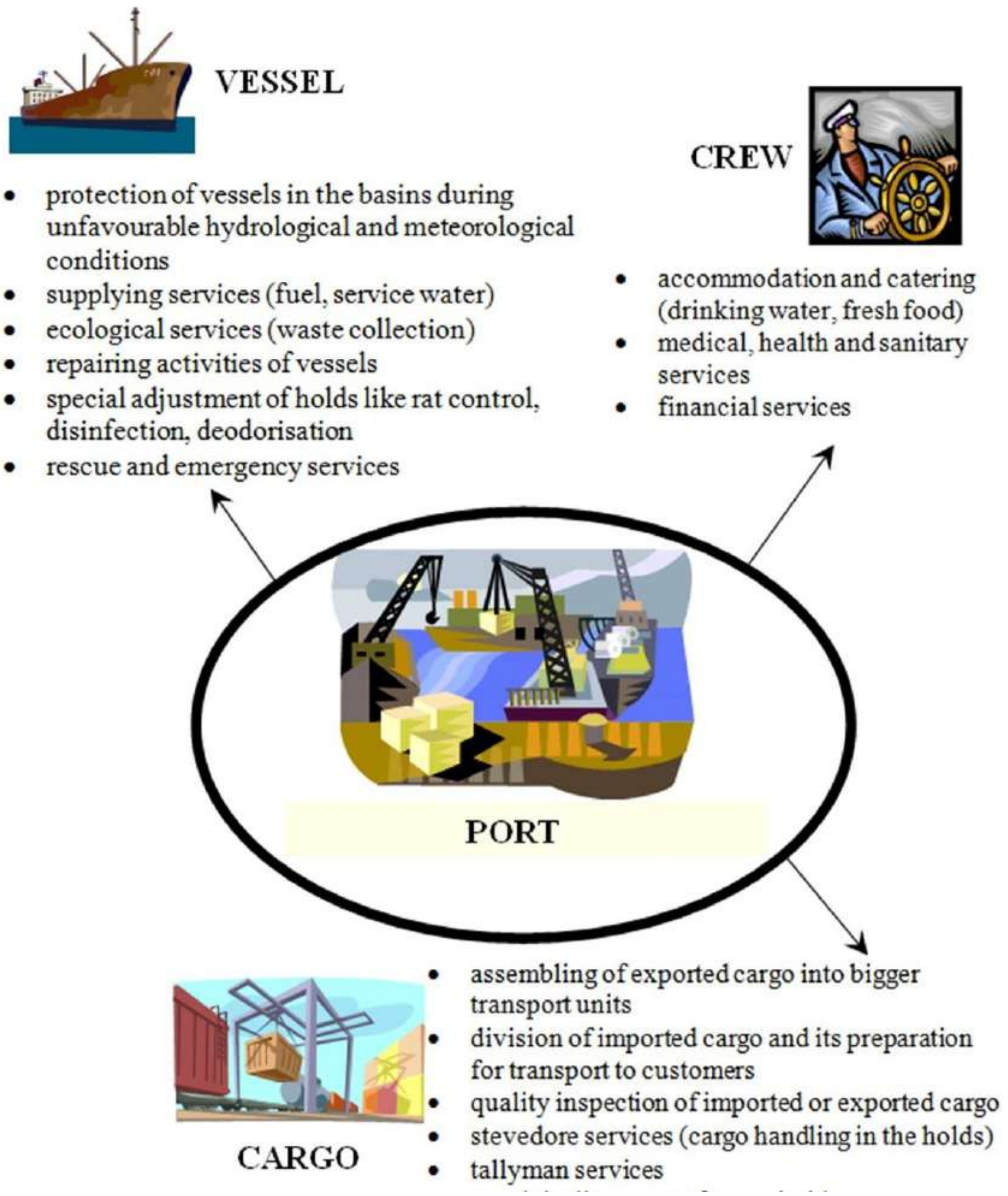

Figure 1. Services provided by a port (Dávid A. 2023)

2.2 Division of maritime and inland ports

Ports can be classified according to the purpose into the following categories.

1. **Business (public) ports** that transfer bulk, general, and liquid cargo, including containers between vessels and other modes of transport by port cranes. They also store cargo in the warehouses or on the open storage areas, transport it, and pack it for the customers. They usually have a water area and a land area. The port's land is equipped with handling facilities (gantry or container cranes) and infrastructure (roads and railway), enabling cargo transport between the port and its customers. Business ports are situated near big commercial and industrial areas. They are usually divided into various berths according to the type of cargo which is transferred there, for instance, transshipment areas for bulk, general, and liquid cargo, container terminals, Ro-Ro Ramp for cars, and areas for transshipment of oversized or overload cargo.

2. Private companies use **industrial ports** to tranship raw materials and semi-finished or finished products between vessels and the port's land. They are usually equipped with specialized handling facilities.

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3. **Passenger ports** are used for embarking or disembarking passengers between vessels and land. They are usually in the city centers because their area does not occupy too much space.

4. **Shipyard ports** are used for repairing or reconstructing vessels. They are equipped with gantry cranes, ship lifts, dry or floating docks, warehouses, and workshops.

5. **Specialized ports** are designed for particular purposes and unique vessels such as military, army, sport, fishing, or recreation ports.

Business (public) or industrial ports are the most import ports from the point of view of transport (Kubec J. 2003).

3. Energy efficiency and automatization of ports

Energy efficiency is a key aspect of sustainable ports (Savu et al., 2022). It involves optimizing energy use, such as improving the operational efficiency of handling facilities and devicesduring cargo transshipment or implementing alternative fuels like liquefied natural gas (LNG) or renewable sources (Andrejszki et al., 2014).

The optimization of energy use is often achieved by the automatization of handling operations, especially in the container terminals of maritime ports. Automated container terminals have container-handling equipment that works without direct human interaction. Crane drivers have been physically removed or have remained in their cabins. Still, they are not needed for the entire duty cycle – various automated handling equipment handle and transport containers between different container locations.

Figure 2. Automated container terminals in the port of Rotterdam (Dávid A.)

Automated guided vehicles (AGVs) have been transporting containers in container terminals since the beginning of the 1990s. They often carry containers at the water-side transfer area, and occasionally at the land-side transfer area. At the water-side transfer area, they move containers between container gantry cranes, and the container yard is divided into blocks. Automated guided vehicles decrease the downtimes in container terminals and minimize accident rates, the number of port workers, and staff costs. The first AGVs used to have diesel engines. In the last few years, they have been replaced by electric models (e.g., the APM 2 or RWG Terminal located in the port of Rotterdam). The batteries are charged twice a day, and electricity is obtained from renewable sources (wind power plants or solar panels in the port area).

Two types of rail-mounted gantry cranes are used in automated container terminals. The first type, which replaced diesel rubber-tired gantry cranes, transports containers between the water-side transfer area and the container yard, or between the container yard and the land-side transfer area, or places containers into the blocks of the container yard. These blocks are perpendicular to the wharf.

The second type of crane operates at the railway station at the land-side transfer area. It moves containers between wagons and semi-trailer trucks (railway and road transport). These cranes typically have large spans and can stack the containers up to 6 tiers high.

Some automated container terminals worldwide, such as Terminal Patrick in the port of Brisbane, or Terminal TraPac in the port of Los Angeles use automated straddle carriers to handle containers across the entire terminal. These automated straddle carriers replaced diesel straddle carriers operated by port drivers (Agershou, 2004; Tsinker, 2004)

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4. Sustainability of ports from an environmental point of view

Warning messages about climate change are becoming increasingly serious, and all possible measures are needed to jointly mitigate these threats. The maritime sector encompasses all industrial sectors and represents 3% of total global greenhouse gas (GHG) emissions, 13% of nitrogen oxide (NO_x) emissions and 12% of sulphur oxide emissions (SO_x) (Gray et al., 2021). In 2018, the global carbon dioxide (CO_2) emissions of shipping amounted to 1.06 gigatons (Gt) representing a share of 2,89% of global anthropogenic CO_2 emissions. Since 2008, the volume and CO_2 emissions from shipping have decoupled along with improved carbon intensity (mainly in attempts to save on fuel costs). However, in the worst case scenario, CO_2 emissions from merchant vessels could increase in the absence of preventive actions (Friedlingstein et al., 2019). An ambitious greenhouse gas (GHG) strategy by the International Maritime Organization (IMO, 2023) aims to cut the shipping sector`s carbon intensity by up to 40% by 2030 and 70% by 2050 compared to 2008. An even more challenging goal is to achieve 100% carbon emission reduction by 2050 across maritime sector globally. The IMO aims to help increase the energy efficiency of ships by measures such as an Energy Efficiency Design Index (EEDI), Energy Efficiency Existing Ship Index (EEXI) and carbon intensity indicator (CII). Regional targets and regulations have also been set, for example, the FuelEU Maritime Initiative in the EU Green Deal Fit for 55 package (14 July 2021) proposing a maximum limit on the GHG intensity of energy used on-board by ships. The Fit for 55 package also suggests shipping to be included in the EU ‘s Emission Trading System (ETS) (Aakko-Saksa et al., 2023).

Air pollution in ports from berthed vessels has a negative impact on people and nature near the port. Air pollution alone is estimated to cause approximately 6,5 million death a year. Despite the 2020 marine fuel sulphur limit of 0,5%, shipping is estimated to cause 250 000 premature deaths and 3 million cases of childhood asthma a year. Emissions such as particulate matter emission (PM), particle number emission (PN) and black carbon (BC) are particularly harmful. Particle emissions are linked to heart and pulmonary diseases and recently Alzheimer`s disease. Particles may carry species, such as PAHs related to carcinogenic and mutagenic activity (Schünemann et al., 2019). Reactive compounds and metal potentially cause inflammation and tissue damage. The residual fuel use in diesel engines emits exhaust particles with marked oxidative activity on the epithelial lining fluid in the lungs. Ship $PM_{2.5}$ emissions near port communities contribute to a health risk disparity based on ethnicity and income since low-income households are overrepresented in the affected populations near harbors. By further considering that the 40% of global population is settled within 100 km from the coastline and that half of the global tourism develops in coastal areas, it is clear as the impact of ports and shipping pollution represents an important health and social issue (Pivetta et al., 2024).

The European Union (EU) considers green hydrogen as one of the main pillars to be integrated in the future energy systems and it is often proposed as a promising option for decarbonizing industrial port areas (IPA). The role of green hydrogen in decarbonising ports was assessed as irreplaceable in the future. In the future, hydrogen and electricity will be needed in 2050 to ensure the transport of both freight and passengers on Europe ‘s Atlantic coast with only renewable energy. Green hydrogen will be essential to guarantee more sustainable maritime transport along Europe ‘s Atlantic coast. The challenge to achieve this now is the high cost of creating a green hydrogen plant capable of meeting market demand (Pivetta et al., 2024).

But as for now, the equipment for cargo handling and inter-port vehicles (except for railways) is almost entirely powered by oil-fueled internal combustion engines (ICE). It was estimated that port equipment involved in cargo handling activities is responsible for up to 15% of air emissions in port areas. The replacement of ICEs by using the best available technology can pass through three different paths: the adoption of alternative fuels, hybrid systems, and fully electrified ones. The ports of Hamburg and Bremerhaven tested a fuel-cell-powered forklift and hydrogen-fueled ICE straddle carriers. A more flexible solution is proposed in the Port of Antwerp, where a tugboat powered by dual fuel engine (diesel and hydrogen) is under construction (Colarossi et al., 2022).

Alongside hydrogen-fueled fuel cells, equipment electrification can also achieve local zero emissions, coupled with a reduction of global emissions. For instance, by means of life cycle assessment comparison between an ICE-powered yard tractors and their electrified counterparts, it was shown that the electrification of the 50% of the yard tractor fleet operating within the Port of Los Angeles could reduce the pollutant emissions up to 60%. Moreover, the connection of rubber-tired gantry cranes to the grid was found to reduce CO_2 emissions up to 80%. Also, onshore power supply (OPS) could effectively contribute to the reduction of GHG emissions in ports, as 70–100% of emissions in IPA are due to ship traffic. However, the

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installation of new infrastructures is challenged by port grid capacity, high capital investments, operating expenses, and by the different power supply specifications between port grids and vessels (Vichos et al., 2022).

Regarding inter-port transportations, railways are the most electrified mean of transport, but in several circumstances, convoys need to operate disconnected from the grid. Some examples include border crossing, service towards low populated areas, cargo handling on port branch lines or industrial spurs, or for maintenance purposes. In such situations, despite traction can be still supported by adopting battery-based storage systems, batteries cannot cope with the daily energy demand. This is especially true when long working shifts are required or duty cycles peak in power consumption as it happens with cranes and reach stackers. Swappable batteries seem a viable strategy to cover daily usage without recurring to oversize capacity installed on vehicle. Off-grid electrification using battery-based storage systems is currently the primary development path for light good vehicles. Similarly, the overall road transportation sector (light-duty vehicles and passenger cars included) is driven towards electrification by a supportive policy framework (Vichos et al., 2022).

5. Conclusion

Since the second half of the 20th century, maritime and inland ports have undergone considerable transformations due to various global changes. Nowadays, ports are logistics hubs that provide different types of logistics services. Environmental, economic, and social aspects and energy efficiency determine their sustainability. Automatization is considered as a part of energy efficiency. On the one hand, it is necessary to optimize all handling operations through various handling devices in the ports. On the other hand, it is essential to focus on protecting the environment. Maritime transport is one of the biggest polluters of the environment. Polluting gases are produced not only during cargo transporting but also during the anchoring of vessels in the ports waiting for all handling operations or embarking or disembarking of passengers. One way to reduce the volume of these harmful gases is to optimize all logistics operations in the ports.

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References

Aakko-Saksa, P. T., Lehtoranta, K., Kuittinen, N., Järvinen, A., Jalkanen, J. P., Johnson, K., Jung, H., Ntziachristos, L., Gagné, S., Takahashi, C., Karjalainen, P., Rönkkö, T., Timonen, H. (2023). Reduction in greenhouse gas and other emissions from ship engines: Current trends and future options. *Progress in Energy and Combustion Science*. 94, 101055. DOI: https://doi.org/grbddb

Agershou, H. (2004). *Planning and Design of Ports and Marine Terminals*. Thomas Telford Publishing, London.

Andrejszki, T., Gangonells, M., Molnar, E., & Török, Á. (2014). ForFITS: a new help in transport decision making for a sustainable future. Periodica Polytechnica Transportation Engineering, 42(2), 119-124. DOI: https://doi.org/nkbf

Colarossi, D., Lelow, G., Principi, P. (2022). Local energy production scenarios for emissions reduction of pollutants in small-medium ports. *Transportation Research Interdisciplinary Perspectives*. 13, 100554. DOI: https://doi.org/nkbc

Dávid A. (2023). *Vnútrozemské prístavy*. EDIS, Žilina.

Dávid A., Sosedová, J. (2005). Transformácia vnútrozemských prístavov na multimodálne logistické centrá. In: *Zborník príspevkov zo 6. konferencie s medzinárodnou účasťou LOGI 2005 – Komplexní logistické služby v přepravních řetezcích*. Universita Pardubice/DFJP, 15. – 16. 02. 2005, Pardubice. 79–83.

Friedlingstein, P., Jones, M. W., O'Sullivan, M., … Zaehle, S. (2019). Global carbon budget 2019. *Earth System Science Data*. 11(4), 1783–1838. DOI: https://doi.org/ggd7p4

Gray, N., McDonagh, S., O'Shea, R., Smyth, B., Murphy, J. D. (2021). Decarbonising ships, planes and trucks: An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. *Advances in Applied Energy*. 1, 100008. DOI: https://doi.org/gqhxzr

https://doi.org/mmr9

International Maritime Organisation (2023) 2023 IMO Strategy on Reduction of GHG Emissions from Ships. URL: https://www.imo.org/en/OurWork/Environment/Pages/2023-IMO-Strategy-on-Reduction-of-GHG-Emissions-from-Ships.aspx

Kubec J. (1993). *Vodní cesty a přístavy*. VŠDS/ETMAS, Praha.

Maternová, A., Materna, M., & Dávid, A. (2022). Revealing causal factors influencing sustainable and safe navigation in central Europe. *Sustainability*, 14(4), 2231. DOI: https://doi.org/mmsb

https://doi.org/10.55343/CogSust.119

Maternová, A., Materna, M., Dávid, A., Török, A., & Švábová, L. (2023). Human error analysis and fatality prediction in maritime accidents. *Journal of Marine Science and Engineering*, 11(12), 2287. DOI: https://doi.org/mmr7

Pivetta, D., Dall'Armi, C., Sandrin, P., Bogar, M., Taccani, R. (2024). The role of hydrogen as enabler of industrial port area decarbonization. In *Renewable and Sustainable Energy Reviews*. 189 Part B, 113912. DOI: https://doi.org/gtr9dx

Savu, S. V., Marin, R. C., David, A., Olei, A. B., Dumitru, I., Tarnita, D., ... & Savu, I. D. (2022). Reducing NO_x emissions through microwave heating of aftertreatment systems for sustainable transport in the inland waterway sector. *Sustainability*, 14(7), 4156. DOI:

Schünemann, H. J., Lerda, D., Dimitrova, N., … Saz-Parkinson, Z. (2019). Methods for Development of the European Commission Initiative on Breast Cancer Guidelines. *Annals of Internal Medicine*. 171(4), 273–280. DOI: https://doi.org/gjdzwg

Tsinker. G. P. (ed.) (2004). *Port Engineering: Planing, Construction, Maintenance, and Security*. John Wiley and Sons, Hoboken, NJ.

Vichos, E., Sifakis, N., Tsoutsos, T. (2022). Challenges of integrating hydrogen energy storage systems into nearly zero-energy ports. *Energy*. 241, 122878. DOI: https://doi.org/gnz8fv

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Enhancing Low Temperature Combustion Through the Application of Alcohol Blends

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Abstract
Future road transportation requires innovative propulsion technologies to address the environmental issues associated with internal combustion engines. Low temperature combustion (LTC) is a new, highly investigated technology capable of simultaneously reducing nitrogen oxide and particulate matter emissions. However, the low combustion temperature in LTC can impair oxidation, limiting its effectiveness under various operating conditions. This paper aims to investigate the effects of oxygenates, particularly alcohols, on LTC to mitigate oxidation difficulties. To demonstrate the effects of alcohols, modulated kinetics (MK) type LTC was achieved in an unmodified diesel engine by applying high rates of low-pressure exhaust gas recirculation at three different loads at 1250 rpm. The combustion and emission characteristics of the engine were evaluated during MK operation using a diesel reference fuel, a diesel-alcohol blend with 30% ethanol, and another diesel-alcohol blend with 30% 2-ethylhexanol. Both alcohols reduced particulate matter emissions and enabled a higher LTC operating range. It was concluded that introducing oxygenated fuels could be advantageous when commercial vehicles utilizing LTC become prevalent, as new combustion technologies necessitate fuels with specific characteristics for optimal performance.

Keywords
Low Temperature Combustion, Modulated Kinetics, Oxygenated Fuels, Alcohols

1. Introduction

Heavy-duty diesel engines are widely applied in many sectors of mobility, such as maritime or road transport. Despite the apparent environmental issues of this technology, there are no other competitive alternatives due to their low costs, high reliability, and well-built infrastructure. Instead of searching for entirely different alternative technologies, the investigation of other supplementary technologies could provide a faster solution to environmental concerns. The two main problems are the air pollution resulting from the high nitrogen oxide (NO_x) and particulate matter (PM) emissions of diesel engines and the greenhouse gas production from fossil fuels. Low temperature combustion (LTC) is a new combustion technology that focuses on the problem of air pollution since it enables a better NO_x-PM trade-off (Singh and Agarwal, 2012). This technique utilizes a homogeneous lean charge that is autoignited in the presence of high amount of residual gases (Krishnamoorthi et al., 2019). The autoignited homogeneous charge burns with a rapid volumetric combustion, but the slowing effects of residual gases keep the pressure gradients in a feasible range (Agarwal et al., 2017). The high heat capacity of the recirculated exhaust gases lowers the combustion temperature; thus, the generation of NO_x through the Zeldovich mechanism is reduced (Zeldovich, 1946). Besides NO_x reduction, PM emission is also reduced due to the mixture homogeneity, which impedes soot formation. Although the technology provides many benefits, it also raises many issues (Singh and Agarwal, 2018). The pressure gradients at higher loads can rise to unacceptable levels, and the mixture can become too lean at lower loads,

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resulting in high cyclic variations or even misfires. Thus, the operating range of LTC has lower and upper bounds. The low temperature can also lead to oxidation issues that worsen the emission characteristics of the engine.

There are many different approaches to realize LTC, and each of them creates a compromise between the technique's benefits and demerits. Duan et al. (2021) completed a detailed review of the homogeneous charge compression ignition (HCCI) type LTC technology, which is one of the most investigated methods. Controlling combustion is a challenging task since the compression ignition of a perfectly homogeneous charge cannot be controlled using the usual direct methods. They concluded that techniques that apply stratification in the combustion chamber can lead to better LTC operation.

Li et al. (2017) wrote a review on the reactivity controlled compression ignition (RCCI). RCCI is a technology that applies a dual fuel strategy to create stratified reactivity in the combustion chamber. They concluded that this method could help control combustion. However, the main benefit is the enlarged LTC operating range; since the stratification allows slower combustion, thus higher loads become feasible. Lawler et al. (2017) and Rahimi Boldaji et al. (2018) investigated thermally stratified compression ignition (TSCI), which is another similar approach. Thermal stratification is achieved by water injection, and the operating range can be extended similarly. Moreover, the water injection can retard the combustion since the water cools the charge. Therefore, the control of combustion becomes easier. However, these techniques require additional expensive systems on the engine.

As a consequence, other researchers investigated simpler methods. These methods usually reduce the degree of homogeneity to gain more control over the combustion and extend the operating range. Hoang (2020) investigated premixed charge compression ignition (PCCI), which uses a premixed charge instead of a homogeneous charge. He pointed out that creating a premixed charge with the early direct injection can lead to increased wall impingement. Thus, a narrow cone angle injector is required to aim the fuel spray on the piston bowl. Lee and Huh (2014) created a premixed charge with a different approach. They applied normal injection timings and extremely high rates of cooled exhaust gas recirculation (EGR) along with high swirl in the combustion chamber. This caused a prolonged ignition delay, and the fuel had time to form a premixed charge with the air, resulting in LTC. This technique is called modulated kinetics (MK), and in our previous research we also studied it. In our latest work (Virt and Zöldy, 2024a), we concluded that the MK is the best type of LTC if no engine modification is possible. However, we experienced a highly limited operating range due to the extremely high EGR rates and the relatively short time available for mixing.

The LTC can be an excellent approach to solve the environmental problems of internal combustion engines. However there is another promising technology: the oxygenated e-fuels. E-fuels are carbon-neutral synthetic fuels produced by utilizing renewable energy and sustainable feedstocks. The feedstock can be waste-based biomass that does not lead to direct or indirect land use changes, carbon dioxide captured directly from the air, and green hydrogen generated with renewable energy (Wicke et al., 2012). Usually, syngas is created from these feedstocks, and properly engineered e-fuels are generated through catalytic processes. A typical example is the Fischer–Tropsch process, which can produce excellent fuel alternatives (Pastor et al., 2020). Due to the renewable feedstocks, carbon neutrality is guaranteed by the carbon cycle (Prentice et al., 2001). Besides carbon neutrality, the reduction of air pollution is also substantial. The application of oxygenates is a widely investigated solution that can reduce PM emissions by aiding the oxidation of local inhomogeneities. A good example is oxymethylene ether (OME), an e-fuel with extremely high oxygen concentration.

Liu et al. (2022) published a review on the effects of OME. They concluded that OME is able to reduce PM emissions significantly. Among other aspects, high oxygen concentration is key since the generated solid particles can be oxidized more easily during combustion. This also leads to a better NO_x-PM compromise; thus, higher EGR rates can be applied to reduce NO_x emission. The oxygen can also accelerate combustion, leading to increased brake thermal efficiency (BTE). Although, the high oxygen concentration of a fuel may lead to disadvantages as well. The lower heating value becomes even lower as the oxygen concentration increases (Pélerin et al. 2020); therefore, bigger fuel tanks and longer injections or increased rail pressure may be necessary. Polarity might be another challenge, since oxygen can make molecules polar, thus conventional sealing materials in the fuel system may be incompatible with the fuel. The effects of oxygen are usually similar for other oxygenates as well. There are several widely investigated oxygenates, usually ethers such as diethyl ether (Agarwal and Chandra, 2022), or alcohols, such as methanol (Hasan et al., 2021). We also conducted multiple studies with oxygenates. We investigated diesel-OME blends and concluded that OME can highly reduce PM emissions However, fuel characteristics have to be improved to meet the requirements of EN590 (Virt and Arnold, 2022). Later, we introduced n-decanol to the

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diesel-OME blends, and the fuel characteristics were successfully improved (Virt and Zöldy, 2024b). The material compatibility aspects were also considered, since engine safety is a key factor during engine dyno tests. Based on our material compatibility assessments, we defined precautions to ensure the safe testing of polar fuels (Virt and Zöldy, 2024c).

Considering the effects of LTC and oxygenated e-fuels, it can be assumed that the two technologies can supplement each other well. Both techniques can improve the NO_x-PM trade-off. Thus, even better emission characteristics can be expected. The LTC has oxidation problems due to the lean mixture and the high EGR rates. Oxygenates can help the oxidation locally; thus, better LTC may be achieved. The LTC's positive effects on PM emission can also permit the use of less oxygen in the fuel to achieve the same PM emission levels as normal operation, thus enabling the application of fuels with higher energy density. In addition, both LTC and oxygenated fuels can improve brake thermal efficiency (BTE), which may lead to more economical engine operation. The assumed advantages are significant, so the effects of oxygenates on LTC must be studied. Therefore, this work applies two different alcohols, ethanol and 2-ethylhexanol (2-EH), as oxygenates. Ethanol is a simple alcohol with two carbon atoms. It can be produced as an e-fuel and has a high oxygen concentration; thus, it is a promising material. However, the cetane number of this molecule is too low; therefore, it cannot be mixed into diesel at high concentrations (Zöldy, 2007). 2-EH is a branched alcohol with eight carbon atoms. Due to the longer chain length, it has a higher cetane number, but the blending is still limited. Compared to ethanol, the application of 2-EH as a fuel component is really underinvestigated. However, there exist some studies (Wojcieszyk et al., 2023; Preuß et al. 2021; Munch and Zhang, 2016) that applied 2-EH successfully.

This paper analyses the effects of oxygenates on LTC by blending B7 diesel with 30% ethanol and 30% 2-EH, respectively. The combustion and emissions are investigated at 1250 rpm at 25, 50, and 75 Nm. MK type LTC was achieved by applying high rates of cooled low-pressure exhaust gas recirculation (LP-EGR). The test fuels and the measurement methods are described in Section 2. Section 3 presents and analyses the results in the studied steady-state conditions. The engine's performance is investigated during MK operation with and without alcohol blending. Besides the NO_x and PM emissions, the heat release rates (HRRs), combustion timings, combustion durations, and peak pressure rise rates are presented.

2. Materials and Methods

2.1. Test Fuels

The blends investigated in this work consist of three components: commercial B7 diesel, ethanol, and 2-ethylhexanol. The ethanol's purity is 98.46 vol%, and the remaining volume is mostly ethyl tertiary butyl ether. The 2-EH's purity is over 99 vol%. Two diesel-alcohol blends were formed, each with 30 vol% alcohol concentration. The blend with ethanol is abbreviated with ETA30, and the blend with 2-EH is abbreviated with EHX30. Table 1 presents the properties of the blends and the blending components. The properties of B7 were measured in our previous study (Virt and Zöldy, 2024b). The properties of alcohols are given in the literature (Yanowitz et al., 2014) and the GESTIS Substance Database. The blend properties were calculated with commonly used mixing rules. These are simple linear mixing rules, except for the viscosity that was calculated by the Arrhenius mixing rule (Nour et al., 2022).

Table 1 Properties of the test fuels and blending components

Property	B7	Ethanol	2-EH	ETA30	EHX30
Cetane number [-]	52.7	8.0	23.5	39.9	44.0
Lower heating value [MJ/kg]	45.55	26.7	37.6	40.2	43.2
Density [kg/m^3]	844	790	830	829	840
Kinematic viscosity [mm^2/s]	2.780	1.047	11.810	2.071	4.290
Oxygen concentration [wt%]	1.00	34.73	12.29	10.01	3.71

2.2. Experimental Apparatus and Calculations

The experiment utilized a Cummins ISBe 170 30 turbocharged medium-duty commercial diesel engine, which had been employed in several previous studies (Nyerges and Zöldy, 2023; Virt and Nyerges, 2023; Nyerges and Zöldy, 2020). This engine was equipped with a common-rail injection system, an intercooler, and both high-pressure (HP) and low-pressure (LP) EGR systems, and it was mounted on an engine dynamometer. Temperature and pressure were measured at the intake side both before and after the compressor, as well as after the intercooler. On the exhaust side, readings were taken before

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and after the turbine and at the exhaust outlet. Fuel consumption was measured using an AI 2000 gravimetric device. Table 2 presents the engine's main parameters.

The EGR rate was adjusted using the LP-EGR valves along with an exhaust brake. The control of the valves was managed through CAN communication with a dSpace MicroAutoBox DS1401/1505/1506, and the sensor data were transmitted via CAN as well. Combustion analysis was carried out using an AVL indicating system. Cylinder pressure was monitored using an AVL GH13P piezoelectric sensor with a ±0.3% FSO linearity, mounted in the glow plug seat. The crankshaft position was tracked using an AVL 365C crank angle encoder with a resolution of 0.1°CA. The data from the indicating system were processed with an AVL 612 Indi-Smart, an 8-channel device with charge amplifiers for the piezoelectric sensors. AVL IndiCom software was employed to process combustion data, while emission and fuel consumption data were recorded using a Matlab/Simulink model. Oxygen and NO_x levels were measured with a Continental UniNOx-Sensor, accurate to 10 ppm. Exhaust gas opacity was measured with an AVL 439 opacimeter, with a sensitivity of 0.1%. No catalytic converters or diesel particulate filters were used to treat the emissions.

Table 2 Cummins ISBe 170 30 main parameters

Displacement	3922 cm^3
Bore	102 mm
Stroke	120 mm
Compression Ratio	17.3
Rated Effective Power	125 kW

Regarding the calculation methods, we applied the same methods as in our previous article, since the current work is the continuation of that study (Virt and Zöldy, 2024a). The parameters related to combustion are calculated from the cylinder pressure, including the heat release rates that are determined based on the First Law of Thermodynamics (Heywood, 1988). The start of combustion (SoC) is determined by the crank angle at which 5% of the total heat is released. The point at which 90% of the heat is released marks the end of combustion. The duration of combustion (DoC) is calculated as the interval between these two crank angle positions.

3. Results and discussion

3.1. Emissions

The engine was operated based on the findings of our previous experiments (Virt and Zöldy, 2024a). By using the LP-EGR valve and the exhaust brake, 9.5% oxygen concentration was achieved at the intake side, while the engine speed was 1250 rpm and the torque was 25, 50, and 75 Nm. Regarding emissions, the exhaust opacity and NO_x concentration were measured. Since the EGR rate was extremely high, the NO_x emission was nearly zero for all the investigated loads. The sensor recorded NO_x concentrations between 1 and 10 ppm, but these values are lower than the sensor's specified accuracy.

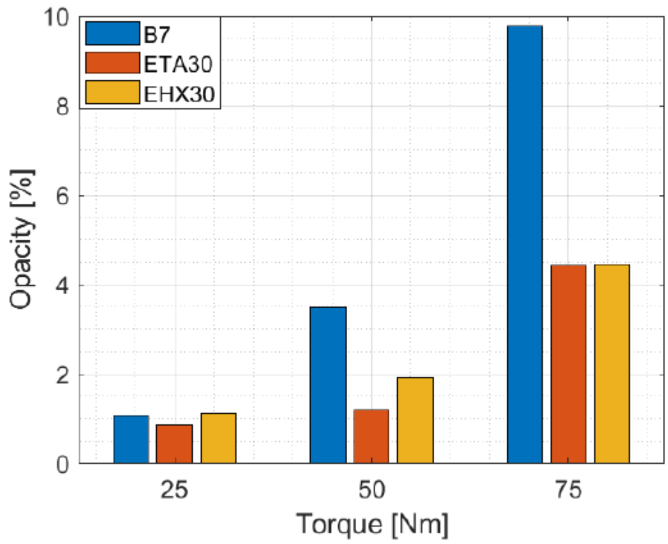

Figure 1. The opacity of the investigated fuels at 1250 rpm with different loads during MK operation

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Figure 1 provides the results of the exhaust opacity measurement. The diesel reference fuel shows a significant increase in sooting, since the dose starts to be too large to properly mix with the air during the ignition delay. This increased heterogeneity leads to increased soot formation, while the oxidation of the generated soot is hindered by the reduced temperature and oxygen concentration caused by the high EGR rate. In the case of oxygenates, oxygen is present in the fuel itself, thus the oxidation of the generated solid particles is easier. It is evident that both diesel-alcohol blends reduced exhaust opacity. The ETA30 blend has three times higher oxygen concentration than the EXH30 blend. Despite this, the ETA30 does not reduce the opacity to a much higher extent than the EHX30.

3.2. Combustion

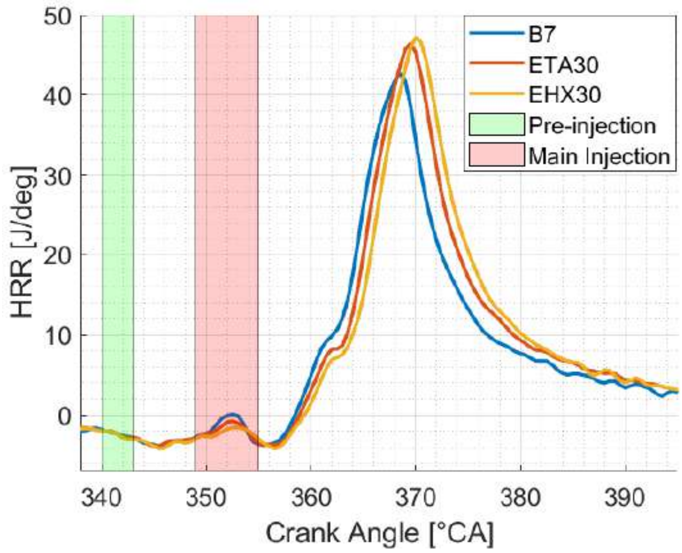

Figure 2. Heat release rates of the investigated fuels at 1250 rpm and 25 Nm during MK operation

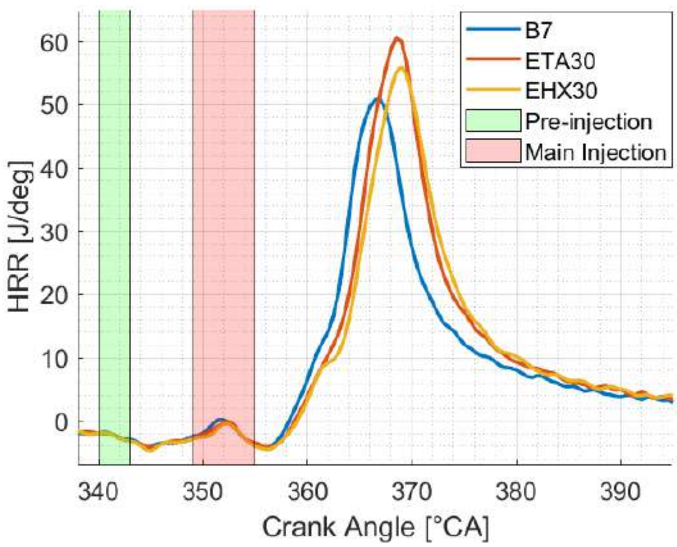

Figure 3. Heat release rates of the investigated fuels at 1250 rpm and 50 Nm during MK operation

Figures 2, 3, and 4 present the heat release rates of the blends at the three investigated loads. The injection strategy was similar in all cases, regardless of the load. The pre-injection happened between 340 and 343°CA, and the main injection was performed between 349 and 355°CA. For higher loads, the higher dose was ensured by the increased injection pressure (around 25 bar increment for each load). The behavior of the fuels is similar for all loads. The heat dissipation of both the pre-and main injection can be observed on the curves. Around 352°CA, a low temperature heat release (LTHR) phase is visible. This is a typical phenomenon of LTC heat release rates when the fuel contains diesel. Here, the combustion has not

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started yet, but some low activation energy reactions are taking place. The combustion begins after the top dead center (TDC). A brake around 362°CA can be observed. This may be a sign that after the first short period of the combustion, the less homogeneous parts of the charge are burning. Regarding the differences between the fuels, it is evident that the combustion of alcohol blends starts slower. This can be attributed to the low cetane number of the alcohols. Despite the lower cetane number of ethanol, the combustion of EHX30 is somewhat slower than that of ETA30. This may be attributed to the much higher viscosity of 2-EH that leads to worsening spray atomization. The peak heat release rate is higher in the case of the alcohol blends. This can be the effect of the higher oxygen concentration. Interestingly, the DoC does not change much. In our previous research with oxygenates, we experienced that the combustion is much shorter when oxygenates are applied (Virt and Arnold, 2022; Virt and Zöldy, 2024b). In these studies, conventional diesel combustion was applied, which had a premixed and a diffusion phase. The fuel's oxygen likely has the most significant accelerating effect during the diffusion phase because it facilitates oxidation in locally rich zones. However, since MK combustion and other LTC techniques are lacking the diffusion phase, the oxygen content of the fuel may not lead to DoC reduction.

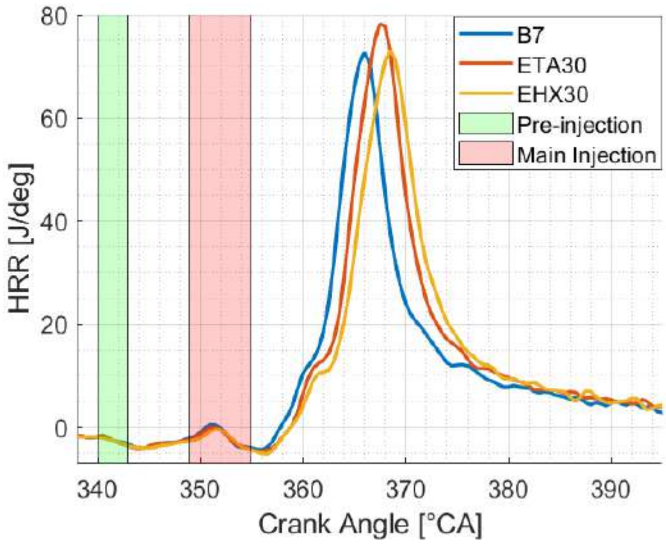

Figure 4. Heat release rates of the investigated fuels at 1250 rpm and 75 Nm during MK operation

Figure 5 demonstrates the start of combustion for the different loads, and Figure 6 presents the center of heat release (CoHR). The values support the previous observations. The SoC is retarded by the low cetane number of the alcohols and the high viscosity of 2-EH. Since the injection strategy is unmodified, the ignition delay changes similarly to the SoC. The change of ID is small, only around 1-2°CA, thus the alcohols does not prolong it so much that a significantly better mixing could be achieved by it. The CoHR results are similar to the SoC results since the DoC did not change that much. The MK combustion leads to a late CoHR that can reduce the BTE compared to normal diesel combustion because work loss can arise due to the late heat release.

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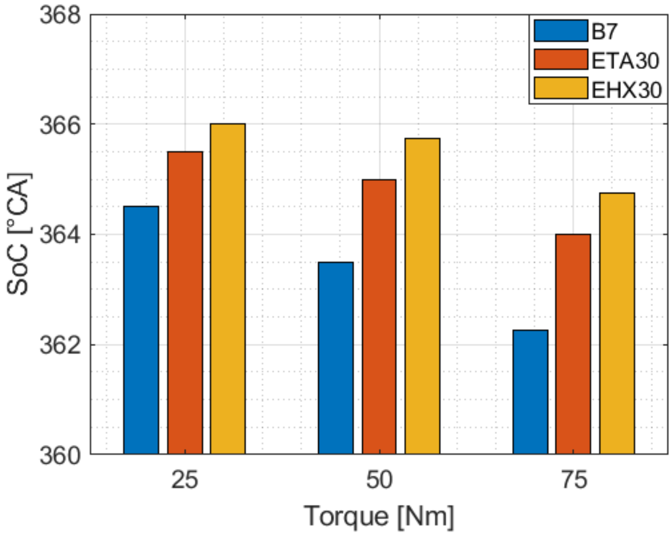

Figure 5. Start of combustion of the investigated fuels at 1250 rpm at different loads during MK operation

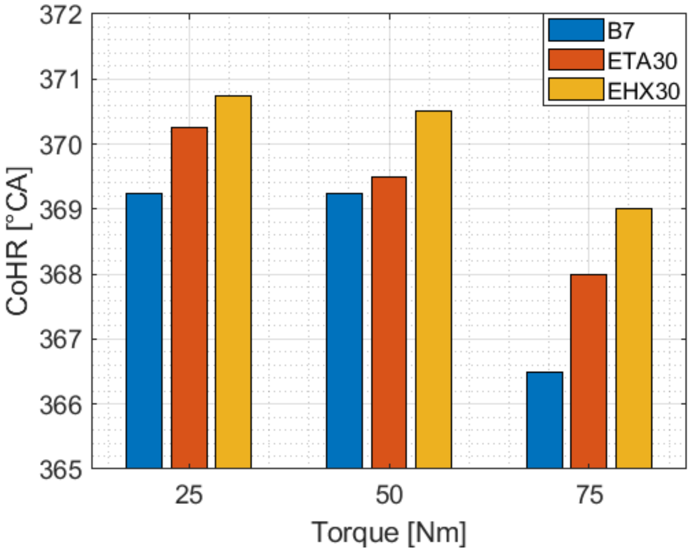

Figure 6. Center of heat release of the investigated fuels at 1250 rpm at different loads during MK operation

Figure 7 outlines the peak pressure rise rate at the different loads. In the case of commercial diesel engines, this value should not exceed 6 bar/°CA to avoid mechanical damage (Yin et al., 2021). The high EGR rate usually leads to slower combustion, although the homogeneous charge of LTC can increase the pressure rise rate. All the values remain well below the given limit and the alcohols tend to reduce the pressure rise rate compared to neat B7 diesel. This may be the effect of the retarded SoC.

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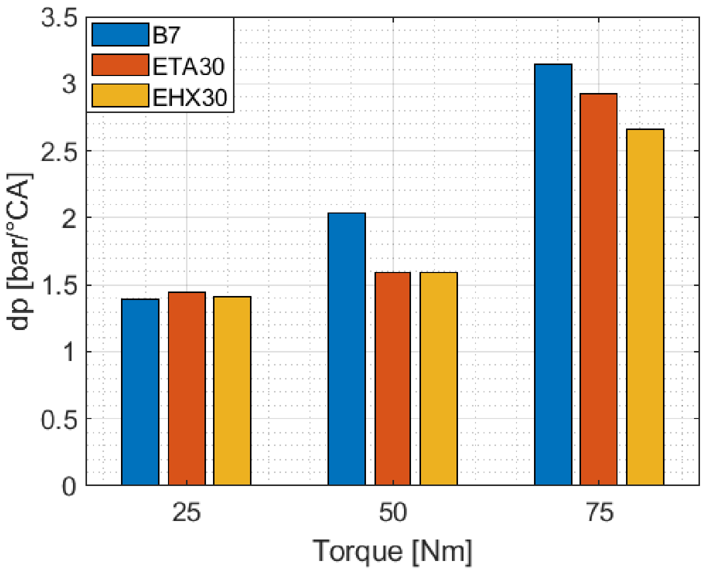

Figure 7. Peak pressure rise rates of the investigated fuels at 1250 rpm at different loads during MK operation

4. Conclusion

This work demonstrated the possibilities of enhancing low temperature combustion by using oxygenated fuels. MK type LTC was realized under three different steady state conditions, and diesel-alcohol blends with ethanol and 2-EH were investigated. It was concluded that these alcohols could improve the LTC. The MK operation has an upper bound for engine load, since high fuel doses cannot mix with air properly during the prolonged ignition delay. The oxygen helped the oxidation and reduced exhaust opacity; thus, this upper bound could be elevated. In contrast to conventional diesel combustion, the DoC did not become notably shorter by adding oxygen to the fuel. In the case of normal engine operation, the oxygen's accelerating effect mainly influences the diffusion phase. This phase is not present in the case of LTC; thus, the combustion is not accelerated that much. This is an advantage, since the rate of pressure rise is a critical parameter for LTC, and increased combustion speed would lead to higher pressure gradients. The investigated blends have relatively low cetane numbers. For MK operation, this can be beneficial, since the ignition delay can be prolonged further. Consequently. higher fuel doses could be used due to the increased mixing time. In conclusion, it was demonstrated that new combustion technologies require new fuel characteristics in order to achieve better operation. The alcohols can be beneficial for LTC due to their high oxygen concentration and lower cetane number. Future investigations should study the effects of even higher oxygen concentrations, for example by applying oxymethylene ether. Moreover, blends with higher alcohol ratios should also be investigated to examine the MK operation with lower cetane numbers. The MK type LTC does not require any engine modification, but it is an inadequate LTC technology due to the highly limited operating conditions. The effects of oxygenates should also be investigated by applying other LTC technologies, such as HCCI or PCCI.

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References

Agarwal, A. K., Chandra, K. (2022). Di-ethyl ether-diesel blends fuelled off-road tractor engine: Part-I: Technical feasibility. *Fuel*. 308, 121972. DOI: https://doi.org/nj9z

Agarwal, A. K., Singh, A. P., Maurya, R. K. (2017). Evolution, challenges and path forward for low temperature combustion engines. *Progress in Energy and Combustion Science*. 61, 1–56. DOI: https://doi.org/m5vx

Duan, X. Lai, M., Jansons, M., Guo, G., Liu, J. (2021). A review of controlling strategies of the ignition timing and combustion phase in homogeneous charge compression ignition (HCCI) engine. *Fuel*. 285, 119142. DOI: https://doi.org/gm2qng

Hasan, A. O., Osman, A. I., Al-Muhtaseb, A. H., Al-Rawashdeh, H., Abu-jrai, A., Ahmad, R., Gomaa, M. R., Deka, T. J., Rooney, D. W. (2021). An experimental study of engine characteristics and tailpipe emissions from modern DI diesel engine fuelled with methanol/diesel blends. *Fuel Processing Technology*. 220, 106901. DOI: https://doi.org/gj5zft

Heywood, J.B. (1988). *Internal Combustion Engine Fundamentals*. McGraw-Hill: New York, NY, USA

Hoang, A. T. (2020). Critical review on the characteristics of performance, combustion and emissions of PCCI engine controlled by early injection strategy based on narrow-angle direct injection (NADI). *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*. 1–15. DOI: https://doi.org/ghwcdn

Krishnamoorthi, M., Malayalamurthi, R., He, Z. Kandasamy, S. (2019). A review on low temperature combustion engines: Performance, combustion and emission characteristics. *Renewable and Sustainable Energy Reviews*. 116, 109404. DOI: https://doi.org/m5v2

Lawler, B., Splitter, D., Szybist, J., Kaul, B. (2017). Thermally Stratified Compression Ignition: A new advanced low temperature combustion mode with load flexibility. *Applied Energy*. 189, 122–132. DOI: https://doi.org/nj93

Lee, Y., Huh, K. Y. (2014) Analysis of different modes of low temperature combustion by ultra-high EGR and modulated kinetics in a heavy duty diesel engine. *Applied Thermal Engineering*. 70(1), 776–787. DOI: https://doi.org/f6gnm2

Li, J., Yang, W., Zhou, D. (2017). Review on the management of RCCI engines. *Renewable and Sustainable Energy Reviews*. 69(C), 65–79. DOI: https://doi.org/f9qwz8

Liu, J., Wang, L., Wang, P., Sun, P., Liu, H., Meng, Z., Zhang, L., Ma, H. (2022). An overview of polyoxymethylene dimethyl ethers as alternative fuel for compression ignition engines. *Fuel*. 318, 123582. DOI: https://doi.org/h8fx

Munch, K., Zhang, T. (2016). A Comparison of Drop-In Diesel Fuel Blends Containing Heavy Alcohols Considering both Engine Properties and Global Warming Potentials. *SAE Technical Paper* 2016-01-2254. DOI: https://doi.org/gbn48s

Nour, M., Nada, S., Li, X. (2022). Experimental study on the combustion performance of a stationary CIDI engine fueled with 1-heptanol-diesel mixtures. *Fuel*. 312. DOI: https://doi.org/nj94

Nyerges, Á., Zöldy, M. (2020). Verification and comparison of nine exhaust gas recirculation mass flow rate estimation methods. *Sensors*. 20(24), 7291. DOI: https://doi.org/f9wg

Nyerges, Á., Zöldy, M. (2023). Ranking of four dual loop EGR modes. *Cognitive Sustainability*. 2(1). DOI: https://doi.org/gr4s8r

Pastor, J., V., García, A., Micó, C., Lewiski, F. (2020). An optical investigation of Fischer–Tropsch diesel and Oxymethylene dimethyl ether impact on combustion process for CI engines. *Applied Energy*. 260, 114238. DOI: https://doi.org/nj95

Pélerin, D., Gaukela, K., Härtl, M., Jacob, E., Wachtmeister, G. (2020). Potentials to simplify the engine system using the alternative diesel fuels oxymethylene ether OME1 and OME3−6 on a heavy-duty engine. *Fuel*. 259, 116231. DOI: https://doi.org/h8f5

Prentice, I. C., Farquhar, G. D., Fasham, M. J. R., Goulden, M. L., Heimann, M., Jaramillo, V. J., Kheshgi, H. S., Le Quéré, C., Scholes, R. J., Wallace, D. W., et al. (2001). The carbon cycle and atmospheric carbon dioxide. In IPCC: *Climate Change: The Scientific Basis, Intergovernmental Panel on Climate Change*. 183–238. URL: https://www.ipcc.ch/site/assets/uploads/2018/02/TAR-03.pdf (accessed on 12 December 2023).

Preuß, J., Munch, K., Denbratt, I. (2021). Performance and emissions of renewable blends with OME3-5 and HVO in heavy duty and light duty compression ignition engines. *Fuel*. 303, 121275. DOI: https://doi.org/gmf4sj

Rahimi Boldaji, M., Sofianopoulos, A., Mamalis, S., Lawler, B. (2018). Effects of Mass, Pressure, and Timing of Injection on the Efficiency and Emissions Characteristics of TSCI Combustion with Direct Water Injection. *SAE Technical Paper* 2018-01-0178. DOI: https://doi.org/m5v4

Singh, A. P., Agarwal, A. K. (2012). Combustion characteristics of diesel HCCI engine: An experimental investigation using external mixture formation technique. *Applied Energy*. 99, 116–125. DOI: https://doi.org/f3995n

Singh, A. P., Agarwal, A. K. (2018). Low-Temperature Combustion: An Advanced Technology for Internal Combustion Engines. In: Srivastava, D., Agarwal, A., Datta, A., Maurya, R. (eds). *Advances in Internal Combustion Engine Research. Energy, Environment, and Sustainability*. Springer, Singapore. DOI: https://doi.org/gjjp9t

Virt, M., Arnold, U. (2022). Effects of Oxymethylene Ether in a Commercial Diesel Engine. *Cognitive Sustainability*, 1(3). DOI: 10.55343/cogsust.20

Virt, M., Nyerges, Á. (2023). Artificial intelligence based simulation of different EGR modes. *2nd International Conference on Cognitive Mobility (COGMOB)*, Budapest, Hungary. 149–154.

Virt, M., Zöldy, M. (2024a). Compatibility Issues of Oxymethylene Ether with Fluorocarbon Rubber Sealings, 6th Global Power, Energy and Communication Conference (GPECOM), Budapest, Hungary. 316–321. DOI: https://doi.org/nj96

Virt, M., Zöldy, M. (2024b). Enhancing the Viability of a Promising E-Fuel: Oxymethylene Ether–Decanol Mixtures. *Energies*. 17(6), 1348, DOI: https://doi.org/nj97

https://doi.org/10.55343/CogSust.121

Virt, M., Zöldy, M. (2024c). Realization of Low Temperature Combustion in an Unmodified Diesel Engine. *Cognitive Sustainability*. 3(2). DOI: https://doi.org/nj98

Wicke, B., Verweij, P., Van Meijl, H., Van Vuuren, D. P., Faaij, A. P. (2012). Indirect land use change: Review of existing models and strategies for mitigation. *Biofuels*, 3, 87–100. DOI: https://doi.org/bfwsc8

Wojcieszyk, M., Kroyan, Y., Kaario, O., Larmi, M. (2023). Prediction of heavy-duty engine performance for renewable fuels based on fuel property characteristics., *Energy*. 285, 129494, DOI: https://doi.org/nj99

Yanowitz, J., Ratcliff, M. A., McCormick, R. L., Taylor, J. D., Murphy, M. J. (2014). *Compendium of Experimental Cetane Numbers*. National Renewable Energy Laboratory. URL: https://www.nrel.gov/docs/fy17osti/67585.pdf (accessed on 12 July 2024).

Yin, X., Li, Z., Yang, B., Sun, T., Wang, Y., Zeng, K. (2021). Experimental study of the combustion characteristics prediction model for a sensor-less closed-loop control in a heavy-duty NG engine. *Fuel*. 300, 120945. DOI: https://doi.org/gjwff5

Zeldovich, Y. B. (1946). The oxidation of nitrogen in combustion and explosions. *Acta Physicochem*., 21, 577–628.

Zöldy M. (2007). Bioethanol-biodiesel-diesel oil blends effect on cetane number and viscosity. *6th International Colloquium Fuels* 2007, Technische Akademie Esslingen.